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THE FABRIC OF A MEDIUM PLASTIC CLAY COMPACTED IN THE LABORATORY AND IN THE FIELD

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PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

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Interim Report

THE FABRIC OF A MEDIUM PLASTIC CLAY COMPACTED IN THE LABORATORY AND IN THE FIELD

TO: H. L. Michael, Director
Joint Highway Research Project

August 26, 1980

Project: C-36-5N

FROM: A. G. Altschaeffl, Research Engineer
Joint Highway Research Project

File: 6-6-14

Attached is an Interim Report on the HPR Part II study entitled "The Effect of Pore Size Distribution on Permeability and Frost Susceptibility of Selected Subgrade Materials". This is the third such report from this study, and it covers the Task D of the approved work plan. It is authored by Dean M. White of our staff.

This report describes the experimental program to define the fabric of the same soil compacted by laboratory and by field procedures. This fabric is believed fundamental to the behavior of the soil in-service and to the prediction of this behavior. Pore-size distribution is used as the measure of the fabric. Descriptors of the distributions were obtained that are statistically related to the compaction variables which produced the fabrics.

The report is submitted as partial fulfillment of the objectives of the study. Copies of the report will also be submitted to ISHC and FHWA for their review, comment and acceptance.

Respectfully submitted,

A. G. Altschaeffl

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Interim Report

THE FABRIC OF A MEDIUM PLASTIC CLAY COMPACTED IN THE LABORATORY AND IN THE FIELD

by

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Graduate Instructor in Research

Joint Highway Research Project
Project No.: C-36-5N
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16. Abstract
The fabric of a medium plastic clay (A-6 soil), as described by its pore-size distribution, was examined for significant differences as produced by different compaction procedures. It is hoped this would improve prediction of field behavior because fabric is said to be the determinant of soil behavior.

The soil had been compacted in a field test embankment for another project by two procedures. It was also compacted in the laboratory by two procedures. Specimens were tested over the broad range of compaction variables. Various descriptors of the pore-size distribution data were examined to see which correlated with their respective variables. The significant descriptors for the different compaction procedures were then compared statistically.

Descriptors involving the logarithm of the 50th and 75th percentile diameters and the percentage of the pore volume that was intruded was found to be the most significant. The magnitudes of the descriptors were significantly affected by how far the compaction water content deviated from the optimum water content; compaction energy-water content interaction terms also were important.

The fabric of the laboratory compacted soil was significantly different from that of the field compacted soil, especially on the dry side of optimum. Laboratory compaction by impact and kneading methods produced the same fabric. The Caterpillar and Rascal equipment used in the field produced different fabrics on the dry side only.

17. Key Words
soil fabric; soil structure; pore-size distribution, laboratory compaction; field compaction

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation officials
ANOVA	analysis of variance
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
cm	centimeters (10^{-2} meters)
ft	foot, feet
g	grams
in	inch, inches
I_p	plasticity index
ISHC	Indiana State Highway Commission
kg	kilograms (10^{3} grams)
lb	pound
m	meter, meters
micron	10^{-6} meters
ml	milliliters (10^{-3} liters)
mm	millimeters (10^{-3} meters)
PSD	pore size distribution
psi	pounds per square inch
sec	seconds
SPSS	Statistical Package for the Social Sciences
sq in	square inches
vpm	vibrations per minute

w_L	liquid limit (%)
w_P	plastic limit (%)

HIGHLIGHT SUMMARY

Densification of soil by mechanical compaction is an effective and efficient means of improving soil behavior for service in the field. The prediction of this behavior in quantitative terms is a concern of the geotechnical engineer. The state-of-the-art suggests that the behavior of laboratory samples can be extrapolated to field soil compacted at similar water content (relative to optimum water content) and to similar dry density. Data indicate this extrapolation is often poor. Test embankments are used on large earthwork projects to establish field behavior, but these are too costly to construct for smaller scale projects.

This study attacks the prediction problem by investigating a possible source of the differences between the laboratory and field compacted earth - the soil fabric. The fabric is characterized by descriptors obtained from measurements of the distribution of the sizes of the voids in the fabric (the pore-size distribution). The freeze-drying, mercury intrusion porosimetry procedure was used to establish the pore size distributions.

The soil was a medium plastic clay (A-6 soil) that had been compacted in a test embankment for a companion project by two different pieces of compaction equipment, i.e., a

Caterpillar Model 825 and a RayGo Rascal Model 420C. In the laboratory, the Proctor impact procedure and the Hveem-type kneading procedure were used for compaction.

Pore-size distribution measurements were taken for replicate samples compacted by the different methods at different water contents (relative to optimum) and energy levels. These measurements were assembled into differential and cumulative pore-size distribution curves. Many possible descriptors of these curves were defined and their magnitudes established by analysis of the curves. This set of descriptors was reduced to a small size for use in regression equations and for comparison of fabric; descriptors with large variance, non-normality, or lack of correlation were discarded.

A peak diameter was found. The diameter at which the peak occurred and the size of the peak changed as the compaction variables were changed. Curve descriptors involving the logarithm of the 50th and 75th percentile diameter and the percentage of the pore volume which was intruded were found to be most significant for use in curve comparisons. The descriptors were most significantly affected by the magnitude of the deviation of the compaction water content from the optimum water content. Compaction energy and energy-water content interaction terms were also significant.

The fabric of the laboratory compacted soil was significantly different from that of the field compacted soil. The difference was more pronounced at water contents on the dry side of optimum and on the wet side; near optimum the differences were less pronounced.

Laboratory compaction by impact and kneading procedures produced the same fabric. Differences in fabric existed on the dry side only (not on the wet side) between the Rascal and Caterpillar field compacted soil.

It appears that the present sensitivity of pore size distribution descriptor values has enabled quanitative comparisons of soil fabric. This suggests several paths for the improvement of field behavior prediction and control using fabric as the guide.

INTRODUCTION

Densification of soil by mechanical compaction has been, and continues to be, an effective and efficient means of improving soil behavior for service in the field. The prediction of this behavior in quantitative terms has been of major concern to the geotechnical engineer.

Much has been written about the behavior of compacted soil, but the a priori prediction of behavior of the field compacted soil has been difficult, at best. Today's state-of-the-art suggests that the behavior of laboratory samples can be extrapolated to field soil compacted at similar density and water content (relative to the optimum water content). This is the case even though the literature also contains data that indicate this extrapolation is questionable. As a consequence, major earthwork projects often contain experimental test embankments from which samples of the field compacted soil can be taken and tested; the field behavior is obtained directly. For smaller scale projects, the prediction difficulty persists since it is usually too costly to construct the expensive test embankments.

This study addresses a fundamental issue in this prediction problem, i.e., the source of the differences

between laboratory and field compacted earth. In clayey soils, the soil fabric is said to be the controlling factor in engineering behavior. This study examines the fabric of the same soil compacted in the laboratory and in the field. The descriptors of the fabric are the distributions of the sizes of the void spaces in the fabric. These sizes are obtained by mercury intrusion procedures which, in studies by Reed (1977) and Garcia-Bengochea (1978), among others, have been shown in good correlation with some behavior characteristics.

Two laboratory compaction methods were used, and two equipment types were used for the field compaction of the same soil. The field operation was for a test embankment being constructed for a different purpose; samples were taken, and specimens were used in this study. The soil was a residual plastic clay classified as an A-6 soil.

Several different results are desired from these studies. Relationships are desired between the compaction variables (density, water content and energy) and pore size distribution parameters for each method of compaction. The search for appropriate distribution parameters is part of this study, as is the determination of whether differences in parameters are significantly dependent upon the method of compaction used. It is then desired to correlate these relationships and predict the field compaction variables which would create the appropriate desired pore size distribution parameters.

The goal of this investigation is to describe the fabric of the soil compacted by different procedures and relate this fabric to the compaction variables. If successful, continuations of the study reported herein can use the fabric descriptors to correlate with behavior properties, and this can be a guide to the prediction of behavior and its control. It is also hoped that a successful correlation of fabric descriptors (for the different compaction methods) can allow the development of the use of laboratory compaction data as direct predictors of field behavior.

A companion study examines the actual behavior properties of the laboratory and field compacted soil. The study reported herein is intended to serve as a bridge between a fundamental explanation of the source of the differences between the laboratory and field compacted soil and the actual quantitative behavior of the soil.

1 - LITERATURE REVIEW AND GENERAL DISCUSSION

1-1 Fabric of Compacted Clays

Systematic studies of soil compaction and the variables which affect the ability to obtain desired behavior in the field were first reported by Proctor (1933). He outlined a procedure for the selection of desirable soil densities and water contents, and a procedure for checking the compacted soil densities in the field. The Proctor procedures for standard compaction tests and the penetration resistance needle are still regularly used in engineering practice today. Examining his results, he attributed the increase in density with increasing water contents up to optimum moisture content to increased lubrication of the soil particles and reduction of capillary forces.

Bennett (1946) suggested that up to the optimum moisture content the water lubricated the soil grains, and at larger water contents a hydrostatic pressure would be produced in the pores of the soil to cause a lower density. He also stated the possibility that it was the film of water surrounding the soil particles and its thickness that might affect the density obtained but developed these ideas no further. He observed that "we can . . . accept

and demonstrate in both the laboratory and the field that the adjustment of the water content at or near the optimum produces the maximum density under a given compactive or rolling effort"; he left the investigation of the structural mechanisms of the soil responsible for this behavior open to discussion.

Papers by Terzaghi (1925), Casagrande (1932) and Hvorslev (1938) had recognized the importance of the arrangement of the soil particles. The nature of the structure* of soil which is responsible for the engineering behavior of compacted clays was perhaps first hypothesized by Mitchell (1956) and Lambe (1958a and b) at M.I.T. using techniques of colloid and crystal chemistry. In his examinations of thin slices of natural clays by optical methods, Mitchell found clay particle orientations to be "the most important fabric component influencing properties", he reported relationships between parallel particle orientation and the permeability and compressibility of the undisturbed and remolded clay. Lambe put these and other observations into the form of a model using double layer concepts originally proposed by Hogentogler (1936). Lambe postulated that the individual clay particles are the predominant

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*Yong and Sheeran (1973) state that "the structure of the soil has been defined as that property of the soil which provides for its integrity" and that "an important component of the structure is its fabric, i.e., the physical arrangement of soil particles including particle spacing and pore size distribution". These definitions of the terms "structure" and "fabric" will be used throughout this report.

units influencing compaction characteristics of a soil mass. The water films surrounding the clay particle (double layer) are suppressed at low water contents resulting in reduced particle repulsion and an open and flocculated state. At larger molding water contents the double layer expands. This increases particle repulsion but results in a more orderly particle arrangement due to increased "lubrication" until optimum water content is reached. The double layer continues to expand at water contents larger than optimum increasing particle repulsion and the distance between particles; this results in a dispersed but nearly parallel particle arrangement.

As the techniques of scanning electron microscopy, x-ray diffraction, and pore size distribution have become more thoroughly applied to soils, modifications to Lambe's model have been proposed.

Investigations by Barden and Sides (1970) and Hodek (1972) independently reached the conclusion that the engineering behavior and characteristics of compacted clay can be explained by a deformable aggregate soil model. In this model, prior to compaction, the soil particles are grouped in peds (aggregations) whose size and strength are dependent on the molding water content. During compaction at low water contents (below optimum), the peds have high strength and resist the pressures of compaction with little deformation. Two networks of pores exist: large pores in the

spaces between peds termed inter-aggregate pores and small pores within the peds termed intra-aggregate pores. As compaction water content increases on the dry side of optimum, the aggregates lose strength and deform under the pressures of compaction. This results in an increase in dry density and decrease in the number of inter-aggregate pores. This decrease in the volume of large pores has been verified by Garcia-Bengochea et al. (1979) and others in pore size distribution measurements on compacted clays.

Olson (1963), and Barden and Sides (1970) found that clays compacted near optimum moisture content have zero air permeability; they say this supports the hypothesis that at this point the aggregates have distorted and fused together to the point of being indistinguishable and that the inter-aggregate voids are no longer an entirely continuous network. Considerable controversy exists on this point and these conclusions must be questioned. Leonards (1975) points out that the degree of saturation below which most of the air voids are interconnected varies significantly--from 80 to 92 percent saturation in typical compacted clays. Interpretations of air permeability measurements should consider these questions carefully. When compaction water content is increased above optimum, the particles in the aggregates of the now fused soil mass may begin to reorient themselves and disperse as Lambe (1958b) originally proposed.

Yong and Sheeran (1973) stated that: "Examination of electron micrographs and soil performance shows that individual particles rarely act as single particle units, ... The different sizes and arrangements of particle groups observed in fabric viewing suggest that response behavior might be controlled by the kinds and arrangements of these particle groups". These observations support the deformable aggregate soil model.

Pore size distribution measurements of compacted clays by Diamond (1970) and (1971), Sridharan et al. (1971), Ahmed et al. (1974), Bhasin (1975), Reed et al. (1979), and Garcia-Bengochea et al. (1979) have supplied strong evidence supporting the deformable aggregate soil model. All of these measurements on laboratory compacted clays including kaolin, illite, Boston blue clay, and others were in general agreement and found that on the dry side of optimum, more pore space is found in the relatively large pores. Bhasin (1975) believes this to be the inter-aggregate pore space which is eliminated at the optimum water content. Bhasin (1975) found that increasing the compactive effort on the dry side decreased porosity and the quantity of large pores, while on the wet side increasing compactive effort had little effect on the pore size distribution or total porosity. Ahmed et al. (1974) found that for Grundite samples, the pore size distributions were affected very little when samples were compacted to a

common water content and dry density by different compaction methods (impact and kneading). Reed (1977) and Garcia-Bengochea (1978) found that only when a high enough percentage of kaolin was present in their silt-kaolin mixes did the deformable aggregate model seem to be valid.

As noted by Garcia-Bengochea (1978), no pore size distribution measurements on field compacted clays have been reported to date. It should also be noted that all pore size distribution samples tested by the authors mentioned above were on almost completely homogenous soils. The soil samples collected and compacted in the field for the pore size distribution measurements presented in this report are to the author's knowledge, the first data of this type reported.

1-2 Pore Size Distribution

The measurement of the pore size distribution of a soil is one technique which allows the engineer to examine the fabric by looking at the relative arrangement of the soil particles. Grain-size criteria have long been used in inferring some engineering properties of a soil. However, it is the pore sizes of the soil which are modified upon shearing, compression, swelling, and frost heaving of soil; these are directly related to the permeability of the soil because it is obvious that the pores are the water transporting media of the soil. Therefore, the author believes

that since measurement of pore size distribution has developed to the point where it can be a simple and routine matter, relating the pore size distribution of a soil to the engineering properties of the soil deserves investigation.

Several methods are available to the investigator of pore size distribution. The gas adsorption technique (or B.E.T. after its developers Brunauer et al. (1938), was used by Aylmore and Quirk (1960); as Sridharan et al. (1971) point out, this technique measures only very small (intra-aggregate) pores and therefore was not of use in this investigation. Csathy and Townsend (1962) used the capillary rise test. This method is slow and takes approximately four weeks per test and is therefore not useful for the large numbers of tests required for an investigation of any size. Gaskin and Raymond (1973) used the pressure plate suction test as one of their methods to determine pore size distribution. The inability to measure pores over large number of orders of magnitude limits this method severely. The mercury intrusion method used in this investigation overcomes the limitations of the above methods and others currently used and follows the lead of other research done at Purdue into pore size distribution. Intrusion with mercury, in that it is a non-wetting fluid, also eliminates the need for an analysis to allocate where the water goes, as is necessary when water is the fluid entering the pores.

The concept of forcing mercury into pores to determine their sizes is not new. Washburn (1921) first proposed this method, suggesting that the pressure, p, required to force a non-wetting liquid, mercury, into a cylindrical pore is inversely proportional to the diameter, d, of that pore as expressed by

$$p = \frac{4\ \sigma_m \cos\theta}{d}$$

where

σ_m = surface tension of mercury,

θ = contact angle between the mercury and pore wall.

This relationship has been examined with respect to the correct values to use for the contact angle and the surface tension (Sarakhov (1963) and others). Even with the limitations noted below the equation is still used in its original form with confidence.

Perhaps the primary limitation of the method is that it does not measure the diameter of the pore itself but rather the diameter of the channel leading into the pore, which conceivably could be smaller. As a result of this "ink bottle" effect, discussed by Ritter and Drake (1945), Orr (1970), and Ahmed (1971), among others, the term "limiting pore diameter" is used to name the diameter which corresponds to the intrusion pressure. It is possible to evaluate the arrangement of ink bottle pores using the second intrusion technique presented by Cebeci et al

(1978). Their work unifies a variety of views on the interpretation of the hysteresis found when measuring intruded volume on the decompression curve; it examines measurements taken on reintrusion of the sample. However, this lengthy procedure was not felt to be justified for this investigation.

Bhasin (1975) also points out that cylindrical pores are assumed by the equation and observes that this assumption is reasonable since differences due to pore shape are well within an order of magnitude while the pore size ranges measured on the compacted soils studied usually extend over five order of magnitude.

Another limitation of the method is that only pores accessible from outside of the sample are penetrated. Kenney (1980) posed this question of continuity of void space in soils in his discussion of Reed et al. (1979); the authors replied (Reed et al. (1980)) that for soils the unintruded space is small and "practically unimportant".

The question of whether or not the soil structure breaks down during intrusion is also of concern as this would change the pore size distribution. Again responding to Kenney (1980), Reed et al. (1980) state: (1) that at the time large pressures are used to intrude small pores, most of the system is filled with relatively incompressible mercury which supports the fabric; and (2) that although the <u>pressures</u> in the pores are large, the <u>forces</u> in the

surrounding soil fabric are more moderate because of the extremely small pore diameters. In addition, the pore size distribution implicitly does not change since the total sample volume, as measured both before and after intrusion, does not change. Further discussion of factors affecting pore size distribution measurements is presented by Ahmed (1971) and Garcia-Bengochea (1978) among others.

Other minor assumptions of the pore size distribution method used include constant contact angle and surface tension values, non-reaction of the mercury with the soil, and incompressibility of the soil fabric. The maximum pressure attainable by the machine used is the only limit to the smallest-sized pore which may be intruded. The 15000 psi capacity of the porosimeter used in this investigation could intrude a pore approximately .016 microns in diameter.

Pore size distribution studies of past investigations have revealed the usefulness of the method in predicting some behavior aspects of soils. Correlations with a variety of other measurements usually made on soils have also been presented. Work has been presented by Marshall (1958) and Garcia-Bengochea (1978), among others which correlate permeability to pore size distribution. Csathy and Townsend (1962), Zoller (1973), Gaskin and Raymond (1973) and Reed (1977) all correlate frost heave rate or amount with pore size distribution. Ahmed et al. (1974)

relate pore size distribution and strength. Sridharan (1968) relates negative pore water pressures to pore size distribution while Ahmed (1971) notes that among the compaction curve variables, molding water content most affects pore size distribution while dry density has the least effect. Sridharan et al. (1971) also point out that there is no obvious correlation between pore size distribution and grain size distribution.

To the author's knowledge, no investigations correlating other engineering parameters to pore size distributions have been presented. This is most probably due to the small number of places in the world carrying out work in pore size distribution of soils. Companion studies to this report will attempt correlations of pore size distribution with engineering behavior properties of field and laboratory compacted soils.

A considerable study of the pore size distribution of portland cement and concrete aggregates has also been completed. Literature on this subject will not be treated here but was examined by Kaneuji (1978) and his references.

1-3 Soil Drying Methods

Since the measurement of the pore size distribution of a soil by the mercury intrusion method requires a dry sample, careful choice must be made to select a method of drying the soils which mitigates alteration of the soil structure while removing the pore water. Several methods

have been developed to dehydrate samples.

Air or oven drying is the simplest method of dehydration and was used by Diamond (1970) and Sridharan et al. (1971). The authors carried out extensive checking and the oven drying method was found not to affect their soils adversely; however, the method is usually unacceptable since the menisci formed as the water exits the pores usually produce forces which are large enough to break down the soil structure, causing shrinkage and cracking.

The fluid replacement method or substitution drying is discussed by Tovey and Yan (1973). The method involves replacing the pore water with another fluid, usually an organic liquid. This fluid is then removed by a simple method (oven-drying) but the menisci which form during this process are not strong enough to break down the soil structure. However, some alignment of particles may take place during fluid substitution and for this reason and the complication of the process fluid replacement was not deemed suitable as a drying method for large investigations.

Critical region drying is a complex procedure and was detailed and used by Bhasin (1975) in his investigations. It involves raising the temperature and pressure of a soil specimen to the critical point of water, at which point the gas and liquid water exist in a single phase. With the critical region of water having been reached, the pressure and temperature of the gas are lowered to

atmospheric in a way such that the water remains in a gas phase. This method eliminates the air-water menisci and shrinkage forces which destroy the soil structure; in this sense it is a very good procedure. However, the high temperatures and pressures used could change the mineralogy of the soil.

Freeze drying was used to remove water from the soil in this study and many others. It is probably most widely used for dehydration for pore size distribution due to its relative simplicity and good preservation of soil structure. Zimmie et al. (1976) and Ahmed (1971) describe the thoery and process in detail. Basically, the soil is quickly frozen to very low (cryogenic) temperatures. This quick freezing eliminates frost heaving and swelling and minimizes ice crystal nucleation and water migration. Once the soil is frozen, it is quickly placed in a vacuum where the water sublimates. Zimmie et al. (1976) point out that the sublimation process keeps the sample sufficiently cool to keep it below the triple point of water so that this operation may be conducted without cooling the vacuum chamber. This drying method also eliminates the air-water menisci shrinkage forces which destroy the soil structure. It is important to control the freezing and drying processes carefully to avoid swelling or shrinkage which could result from improper freezing or drying, respectively.

Freeze drying of soils has been shown by Diamond (1970), Tovey and Yan (1973), Ahmed et al. (1974), Zimmie et al. (1976), Reed (1977) and Garcia-Bengochea (1978) to be a superior method for removing water if properly conducted, generally keeping volume changes to a maximum of 5%. For this reason and its relative simplicity freeze drying was chosen for use in this investigation.

1-4 Data Presentation

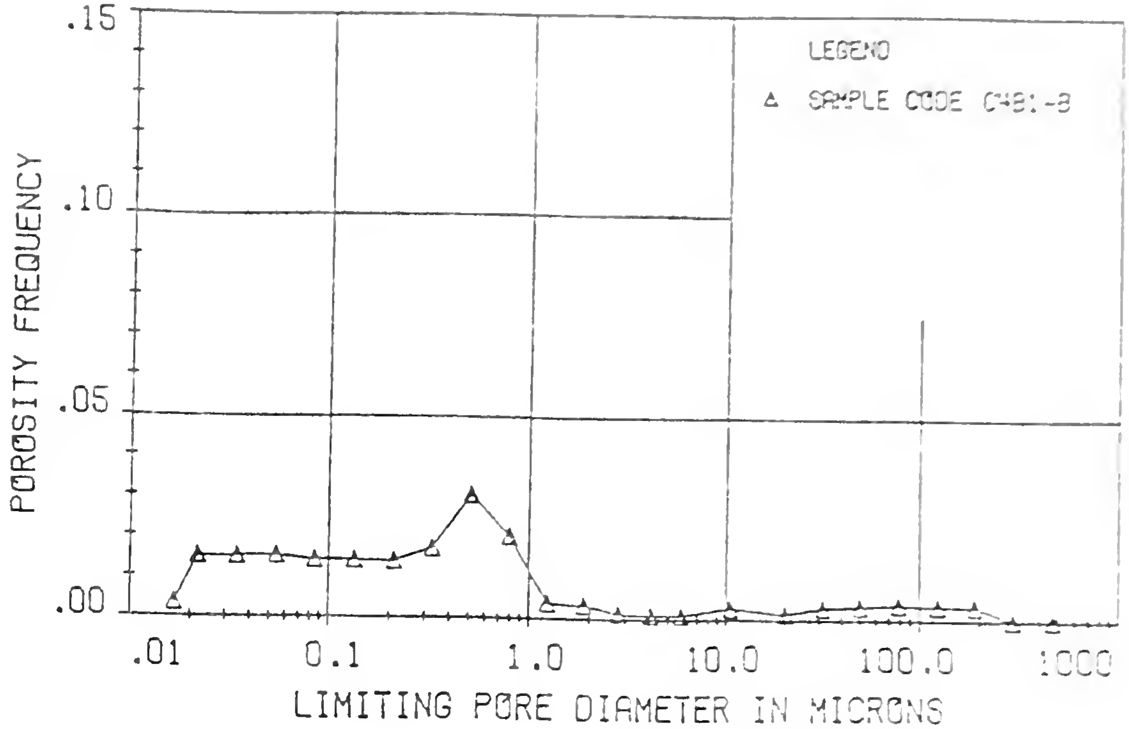
Two standard methods are usually used to graphically present data from pore size distribution measurements. Curves are presented in the form of cumulative and differential distribution curves, each having its own use. Typical curves are shown in Figure 1.1. The cumulative distribution is used to find:

1) total porosity of sample,
2) percent of pore space intruded, and
3) percentiles of pore diameters (fraction of pore space greater or smaller than a given size).

The differential distribution shows:

1) general type of distribution,
2) most frequent pore size, and
3) gaps and irregularities in the data.

Some of the items listed above are themselves quantitative measures of the pore size distribution curve or can be used to calculate such quantitative measures. The choice of what quantitative measure to use to represent the curves is



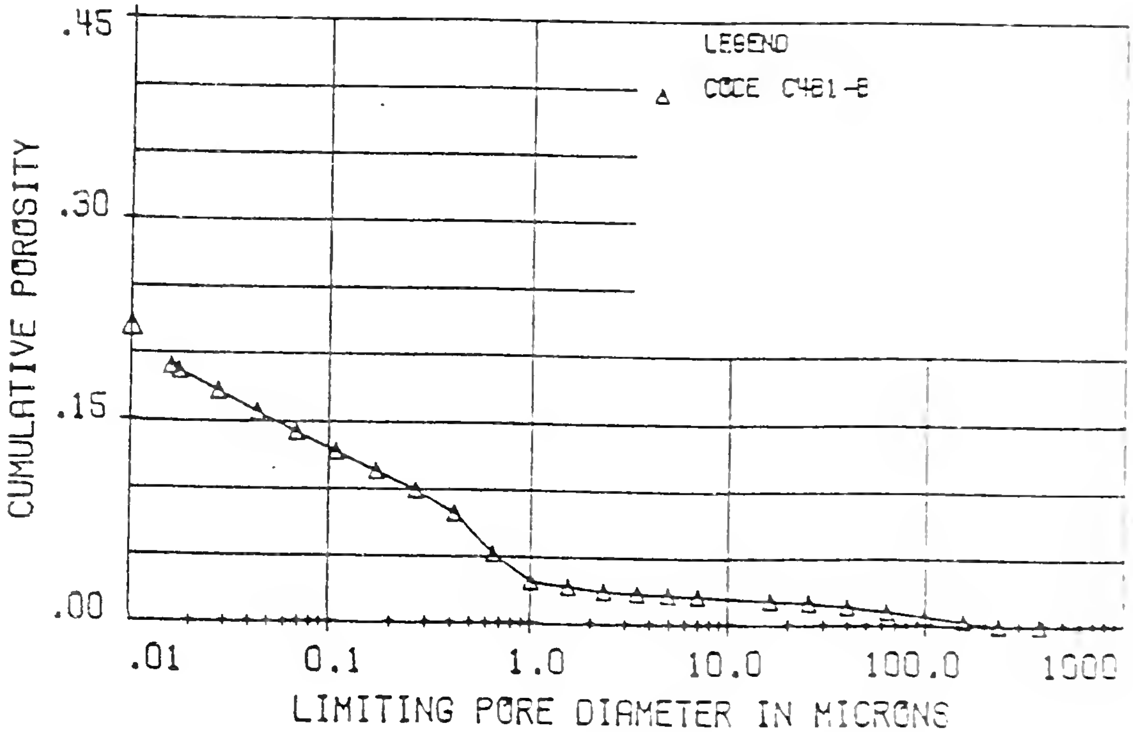


Figure 1.1 Example Pore Size Distribution Curves

quite important and a significant part of this study. Statistical correlations are heavily reliant on numerical parameters which show the important likenesses and differences among the pore size distributions. Previous writers have used a variety of pore size distribution parameters for correlations as listed in Table 1.1. These and other parameters developed by the author were used in attempts to describe the curves obtained in this study. This variety of parameters permits a wide choice for use in the description of pore size distribution curves. Use of many parameters in a statistical model adds precision to the predictions obtained from the model, but for facility of use a simple, easily understood parameter or set of parameters is desired for correlations.

Table 1.1 Pore Size Distribution Parameters

Parameter	Author	Exploration
D_{50}	many	diameter where 50% of pore volume is in larger pores; 50-percentile diameter
D_{25}	many	25-percentile diameter as in D_{50}
D_{50}/D_{25}	Kaneuji (1978)	"spread factor"; ratio of 25-percentile and 50-percentile diameters
D_{40}/D_{80}	Reed (1977)	ratio similar to above D_{50}/D_{25}
P_{90}/P_{70}	Csathy & Townsend (1962)	same as D_{10}/D_{30}
$X_{3.0}$	Reed (1977)	percent porosity in pores larger than 3.0 microns
$X_{0.4}$	Reed (1977)	percent porosity in pores larger than 0.4 microns as in $X_{3.0}$
$\frac{X_{3.0}}{X_o \cdot X_{0.4}}$	Reed (1977)	successful parameter for frost heave
PV, X_o	many	intruded pore volume in cc/g
PSP	Garcia-Bengochea (1978	parameters using moments of areas under frequency plot

2 - APPARATUS AND EXPERIMENTAL PROCEDURE

2-1 Soil Studied

The soil used for both the laboratory and field compaction in this study was a medium plastic clay, given the name St. Croix clay. The soil was removed from a cut made as a part of a realignment project of State Road 37, approximately four miles south of St. Croix, Indiana. It was a residual soil of shale and sandstone origin, and had numerous friable pieces of sandstone of various size throughout the mass. It was tan in color, with gray and red mottling. Pertinent quantitative data are shown in Table 2.1

Table 2.1 Index Properties and Classification of St. Croix Clay

		Field	Lab
Atterberg Limits (%) mean(low,high)	w_L	40.1 (35.3,43.5)	38.3 (37.0,39.2)
	w_p	17.9 (16.2,20.0)	16.3 (15.6,16.7)
	I_p	22.2 (17.0,25.9)	22.0 (20.9,22.7)
Specific Gravity	G_s = 2.75		
Unified Soil Class Proatron	CL		
AASHTO Classification	A-6		

Some variation is present in the Atterberg Limits indicating the inherent variability present in any soil found in the field. From Figure 2.1 a trend towards lower limits can be seen to the north and in the center of the pad grouping. Laboratory variability is lower due to the soil being taken from several locations and mixed together before compaction and testing.

2-2 Field Compacted Samples

2-2.1 Test Pad Construction

Ten test pads were constructed of the test soil in the area of the previously mentioned realignment project of State Road 37 near St. Croix, Indiana in June 1978. Each pad was 14 feet (4.3m) wide and 116 feet (35.4m) long. Figure 2.1 shows the layout of the pads. The test pads

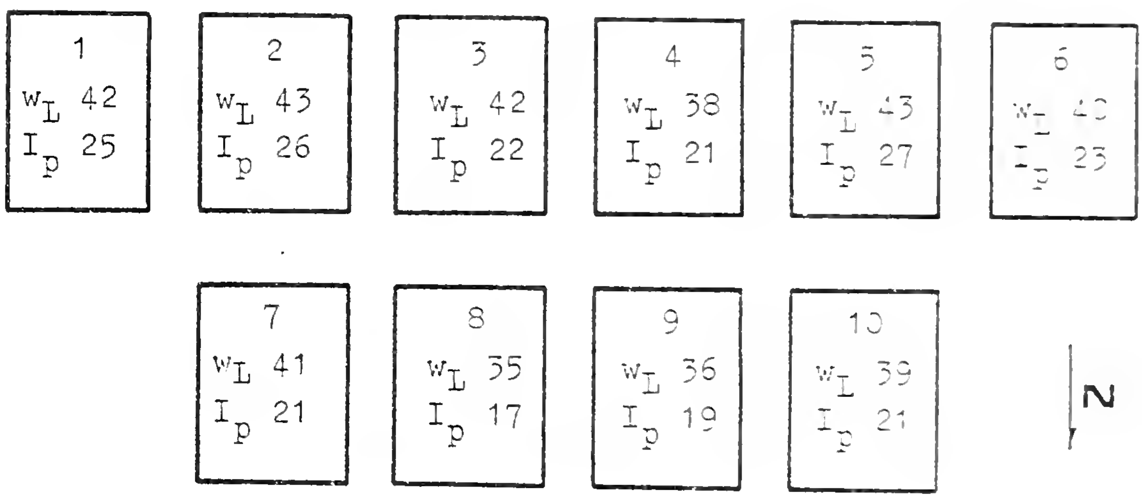


Figure 2.1 Test Pad Layout Showing Atterberg Limit Variation

were placed on a leveled test site in 8 inch (20 cm) lifts. Prior to rolling (compaction) of the test pads water was sprinkled into the loose clay (each pad to different water content) and the area was disked to create homogeneity. The pads were then covered with plastic to cure for approximately ten days.

Five pads were rolled with a Caterpillar Model 825 segmented pad roller and five pads were rolled with a RayCo Rascal Model 420C segmented pad vibrating roller. Samples retrieved from test pads compacted with each of these rollers were designated (C) and (R), respectively. Specifications for the equipment may be found in Table 2.2. The segmental pad (sheepsfoot) type of rollers which were on both pieces of compacting equipment preclude applying a completely uniform compactive effort to each test pad, as is desirable to reduce variability in the test samples retrieved. Obviously, only the intermittent parts of the test pad under each pad on the roller received the maximum energy applied by each pass of the compaction equipment. On subsequent passes the compactor pads may either (a) run over soil previously compacted, (b) run over relatively uncompacted soil, or (c) not run over the uncompacted soil on that pass at all; this produces a wide variation in the compactive effort applied to any given point in the test pad. As the number of passes increases, the process should provide increasing uniformity in compactive effort applied across the test pad but a totally uniform effort should not be expected. Accordingly, variation should be expected in

Table 2.2 Field Compaction Equipment Specifications

RayGo Rascal Model 420C

Length	18 ft-9 in	Weight	25,160 lb
Width	9 ft-0 in	Vibration	hydraulic, direct drive
Height	7 ft-2 in	Frequency	1100-1500 vpm
Wheelbase	9 ft-0 in	Dynamic Force	32,000 lb
Drum Length	84 in	Pad Height	5 in
Drum Diameter	50 in (60 in over pads)	Pad Face Area	13.86 sq in
No. of Pads			
No. of Chevrons	10		
No. of Pads/Chevron	14		

Caterpillar Model 825

Length	23 ft-4 in	Weight	63,000 lb
Width	13 ft-8 in		
Wheelbase	11 ft-8 in		
Drum Length	44½ in	(2 drums/axle)	
Max Ballast/Wheel	244 U.S. gallons		

the dry density measurements at various places within a given test pad. Additional discussion of field compaction variability can be found in Price (1978), among others.

Each test pad was sampled following the completion of 4, 8, and 16 passes of the compaction equipment over the pad. This was done to obtain a set of field moisture-density curves (i.e., field compaction curves) for different energy levels. Samples taken following completion of each set of passes were identified with letters (A), (B), and (C), in order of increasing energy (number of passes) applied.

It was desired to obtain a set of five pads at five different water contents for each method of compaction, with water contents on both the dry side and wet side of the optimum water content; it was hoped to maintain a uniform water content within each test pad. These objectives were not met due to the conditions prevailing in the field. Significant variation in water content was found within each test pad and control over water content was difficult, at best; this was true even with the special measures taken to create the uniformity. Samples taken from the test pads were designated (1) through (5) to identify the water content for the pad from which the sample was taken. The water content planned for each pad was randomly selected so there is no progression of water content with number of test pad.

The ISHC Troxler Model 3401 Nuclear Gauge was used by inserting it at various locations in each test pad to determine the density and moisture content of the soil. Values obtained by the Nuclear Gauge are presented in Table 2.3. The moisture-density curves obtained are plotted in Figures 2.2 and 2.3 for the Caterpillar and Rascal compactors, respectively. Wide variability is quite evident in these plots, most probably due to procedural factors already discussed, measurement errors and the inherent variability present in a soil mass.

2-2.2 Field Sampling

A number of samples (840) was collected from each of the test pads at randomly selected grid locations. Soil used for pore size distribution work was taken from samples collected for use in swelling-pressure measurements, one of the companion studies previously mentioned.

Following completion of the desired number of passes by the compaction equipment, sampling tubes were driven into the ground with a drop hammer at the specified grid location at the bottom of the taper-foot depression made by the roller. The driving apparatus is shown in Figure 2.4. The sampling tubes were manufactured in the Central Machine Shop, Purdue University. The swelling-sample tubes were made from steel having an external diameter of 2.75 inches (6.99 cm) and an internal diameter of 2.51 inches (6.38 cm). They were 5.0 inches (12.7 cm) long and one end was machined to form a

Table 2.3 Density and Moisture Content Values for Test Pads

No. of Passes		4		8		16	
Pad No.	Roller Type	Yd	w	Yd	w	Yd	w
1	R	108.2	22.5	106.9	23.6	111.9	17.0
		95.0	26.0	106.3	19.4	102.6	23.1
		101.7	23.1	103.4	19.2	105.7	21.3
		R5A		R5B		R5C	
2	C	97.2	26.1	101.2	25.1	106.0	22.6
		106.9	23.8	97.7	27.4	106.5	21.3
		100.0	20.0	103.8	21.1	106.5	20.7
		C5A		C5B		C5C	
3	C	103.1	21.2	106.6	20.5	111.6	17.0
		108.0	19.2	100.0	22.7	104.0	21.2
		100.0	22.1	105.5	19.4	99.4	21.4
		C4A		C4B		C4C	
4	C	105.0	10.3	109.1	14.7	107.4	15.4
		104.9	16.3	110.3	12.4	105.9	15.6
		107.4	12.7	103.8	41.0	107.5	14.[illegible]
		C2A		C3B		C4C	
5	R	99.5	20.6	101.2	17.9	103.3	19.0
		99.4	21.1	102.5	25.7	95.6	22.8
		96.9	19.2	101.2	17.9	105.9	17.0
		R4A		R4B		R4C	
6	C	103.2	17.1	108.4	13.7	102.1	15.2
		105.3	15.7	111.5	16.1	108.4	17.2
		105.8	13.9	114.2	14.7	103.9	15.5
		C2A		C2B		C2C	
7	C	98.0	14.8	113.2	15.4	110.25	15.6
		104.0	14.9	109.3	14.5	112.5	16.0
		96.0	16.9	111.1	16.5	112.8	16.8
		C1A		C1B		C1C	
8	R	104.3	17.7	111.9	13.8	105.9	15.1
		98.0	16.6	106.8	12.5	110.7	14.2
		101.8	14.2	102.5	14.9	108.7	15.6
		R3A		R3B		R3C	

Table 2.3 (continued)

No. of Passes							
Pad No.	Roller Type	Yd	w	Yd	w	Yd	w
9	R	98.9	15.7	103.25	16.9	114.5	15.6
		101.7	16.4	107.6	12.9	112.5	14.7
		104.25	14.6	107.4	14.4	106.3	14.5
		R1A		R1B		R1C	
10	R	103.5	14.0	107.6	17.0	111.9	16.5
		98.3	13.0	104.8	15.7	105.3	15.0
		95.9	14.6	106.4	12.9	108.6	15.9
		R3A		R3B		R3C	

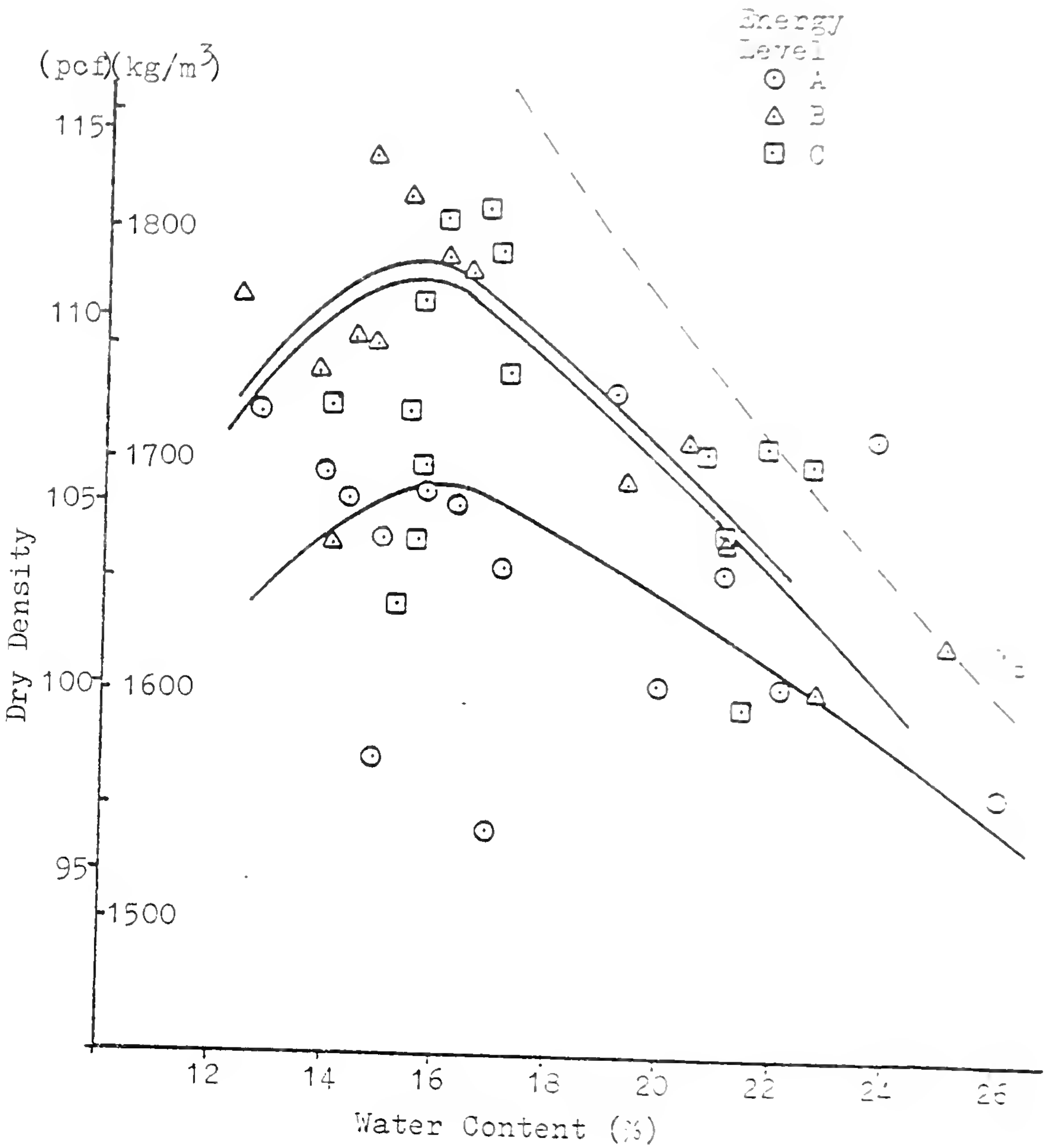


Figure 2.2 Caterpillar Compaction Curves

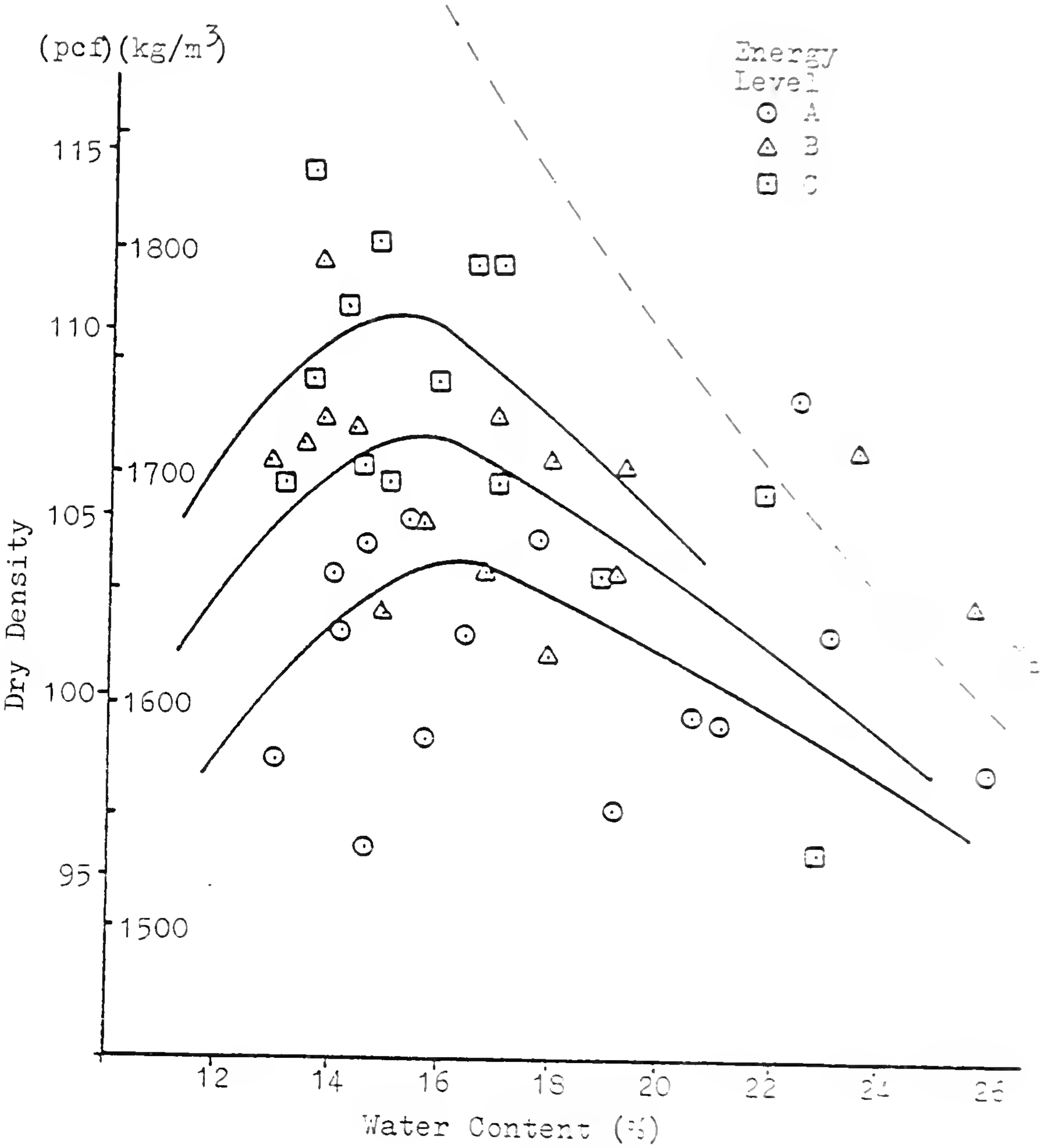


Figure 2.3 Rascal Compaction Curves

Figure 2.4 Sampling Tube and Hammer for Field Sampling

blunt cutting edge. The assembly used to drive the sampling tubes into the compacted soil consisted of (a) a driving head to which the sampling-tube was attached with four set screws, (b) a pipe screwed into the driving head to guide the falling weight, (c) the falling weight, (d) a disk screwed onto the top of the pipe to both hold the hammer and control the height of the fall, and (e) two pieces of wood, one placed between the sampling-tube and hammer to protect the top of the tube and the other placed between the driving head and the falling weight to cushion the impact. In the operation the 16.7 lb (7.6 kg) falling weight fell 28 inches (71 cm). The driving head and its attachments weighed 10.8 lb (4.9 kg) bringing the total weight of the apparatus to 27.5 lb (12.5 kg), light enough to be handled by a single person.

After the sampling-tubes were driven, they were dug out of the pad; the samples were then extruded from the tubes with a hydraulic jack (Figure 2.5) wrapped in plastic covered with cheese-cloth, and finally coated with paraffin. They were then labeled and brought to Purdue University for testing. A label marked R2B5 would indicate the sample was compacted by the Rascal equipment (R) at the second water content (2) and was the fifth sample (5) collected after the equipment made 8 passes (B).

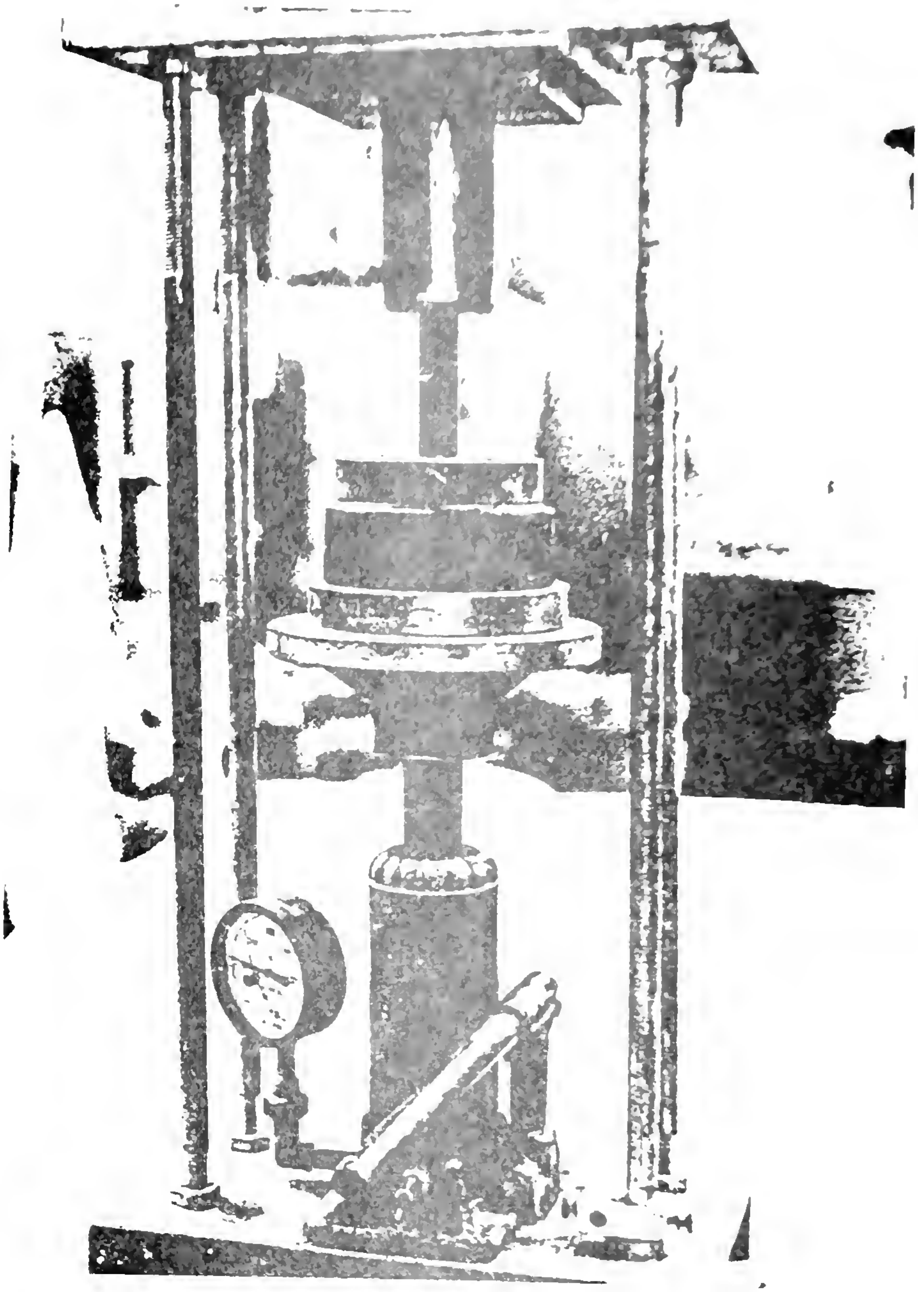


Figure 2.5 Extrusion of Sample from Sampling Tube

These sealed samples were stored until testing in 5 gallon buckets; they were kept humid and padded with shredded foam.

2-3 Laboratory Compacted Samples

2-3.1 Soil Mixing and Curing

At the time of the construction of the test pads in St. Croix in June 1978, a large quantity of the soil used for the test pads was collected from the cut and brought to Purdue University for use in laboratory compaction and testing programs. This soil was stored in 55 gallon garbage cans lined with polyethylene bags; its air-dry water content was approximately 2.5%. The laboratory program was started in January 1980.

Prior to mixing of each laboratory sample, the soil was forced through a No. 4 sieve to remove large stones and obtain a more uniform material. The soil was then mixed to the water content chosen for compaction of that sample. Water contents were chosen to provide a point near the optimum water content and even intervals to both sides for the desired moisture-density curve. A measured quantity of the soil (just enough for the compaction mold) in storage at 2.5% water content was mixed with the required quantity of distilled water in a plastic tub. This was done by wetting the surface of the soil with water sprayed from a hand-operated atomizer while stirring the soil with

a large spoon. This gave an even distribution of the water throughout the sample and minimized the clumping which occurs when mixing by methods which add water in other ways.

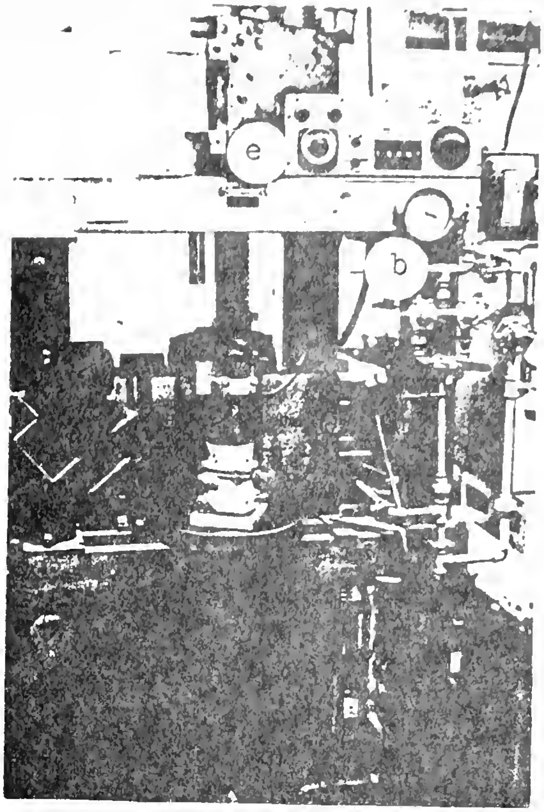
Once the proper amount of water was mixed into the soil, the soil was mixed again very thoroughly and placed in a polyethylene bag to cure for a minimum of 3 days. These bags were then stored in a humid container to further minimize moisture loss. Experience from Weitzel (1979) indicated that 3 days was sufficient time to allow the water to equally distribute itself. Samples were labeled numerically for water content in a manner similar to the field samples.

2-3.2 Laboratory Compaction

Two different methods were used in compacting laboratory samples. A kneading compactor manufactured by the August Manufacturing Company of Oakland, California and shown in Figure 2.6 was used for one set of samples; standard laboratory impact type hammers were used for the other set. Samples compacted by these compactors were designated (K) and (I), respectively, in a labeling system similar to that used for the field samples.

Kneading Compaction

Kneading compaction was chosen to prepare one set of the samples to be tested because: (1) companion studies



a - tamping foot
b - foot pressure gauge and valves
c - rotating table
d - split Proctor mold
e - timer

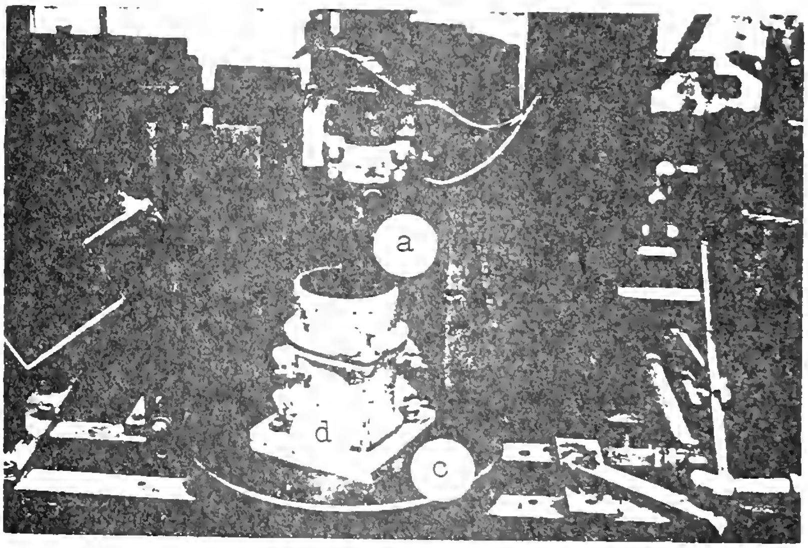


Figure 2.6 Kneading Compactor

in the project used the method, and (2) it is felt that the shearing strains and loading patterns that occur during sample compaction by this method are similar those that were used in the field.

The compactor is an automatic device with mold rotation and foot tamping being driven by an electric motor and foot pressure being supplied by a pneumatic-hydraulic system. Further details of compactor construction and operation are explained by Gaudette (1960).

Samples were compacted at three energy levels (foot pressures) chosen carefully from curves obtained by DiBernardo (1979) for St. Croix clay to duplicate the impact compaction energy levels to be used. The corresponding foot pressures used for kneading compaction are shown in Table 2.4.

Table 2.4 Foot Pressures for Kneading Compaction

Energy Level	Foot Pressure (psi)	Corresponding Impact Test
A	4	Low Energy Proctor
B	7	Standard Proctor
C	26	Modified Proctor

Moisture-density curves obtained for both compaction methods were therefore very similar as is evident in Figures 2.7 and 2.8, the kneading and impact curves, respectively. The data used in plotting these curves are presented in Table 2.5. The energy levels of the curves and samples are labeled (A), (B), and (C) for identification purposes in a manner similar to the field samples.

To compact a sample, a Standard Proctor split mold of 1/30 ft^3 (944 cm^3) with a collar (see Figure 2.9) was bolted to the rotating table of the machine. Soil at the desired water content was taken from the polyethylene storage bags, sampled for water content, and spooned into the mold. The soil was compacted in five layers of approximately equal thickness. Each layer received 30 tamps from the foot in one minute. The mold was rotated 60 degrees between tamps, allowing full face coverage of the sample by 6 tamps. The amount of pressure exerted by each tamp was controlled by a system of valves between the foot and air pressure source and was carefully regulated to the values in Table 2.4. Between layers the top of the compacted layer of soil was scarified to ensure sample homogeneity. This was especially crucial for the drier, high-energy samples. The fifth and final layer brought the soil to a level slightly higher than the top of the mold. The mold was then unbolted from the compactor table, the collar was

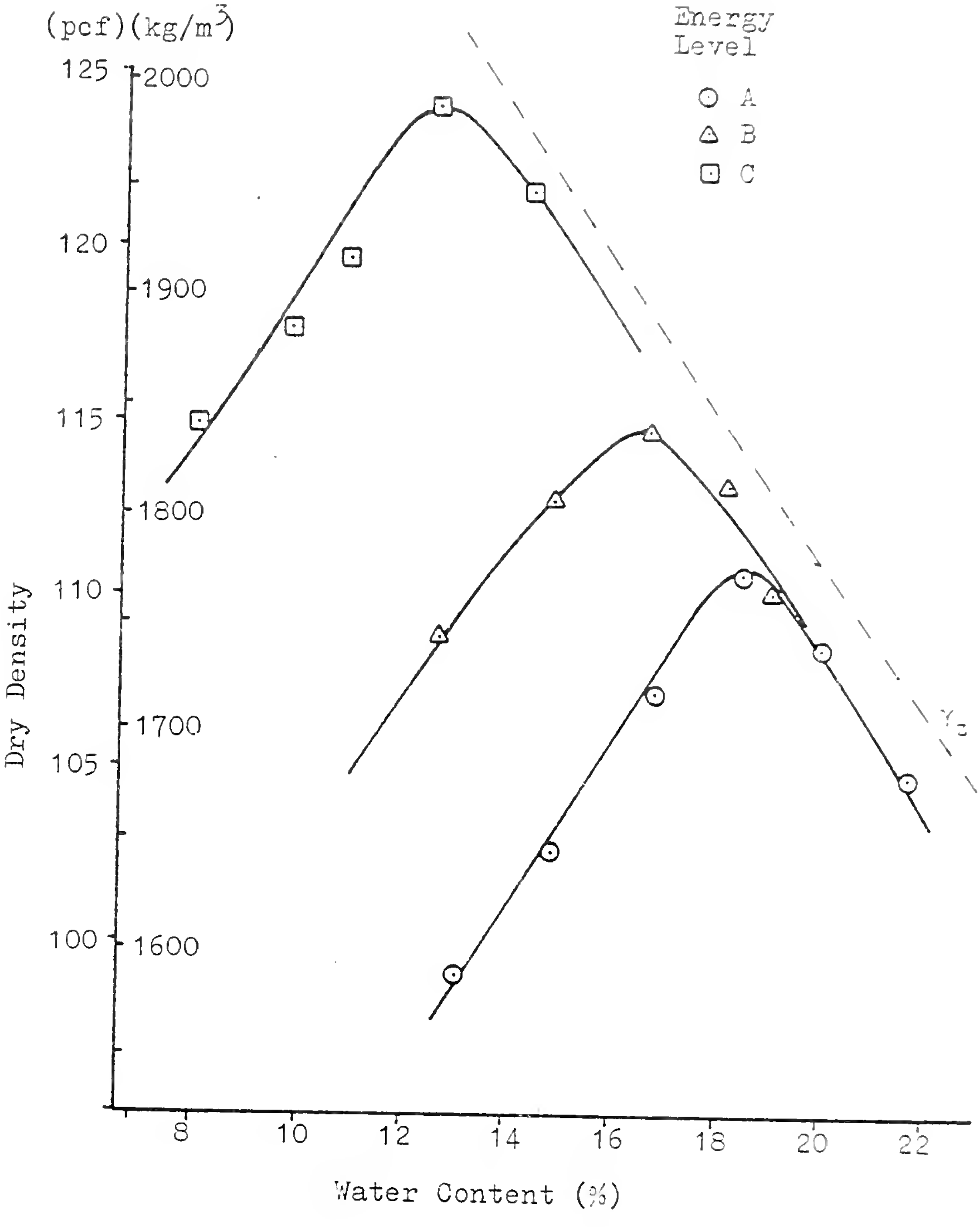


Figure 2.7 Kneading Compaction Curves

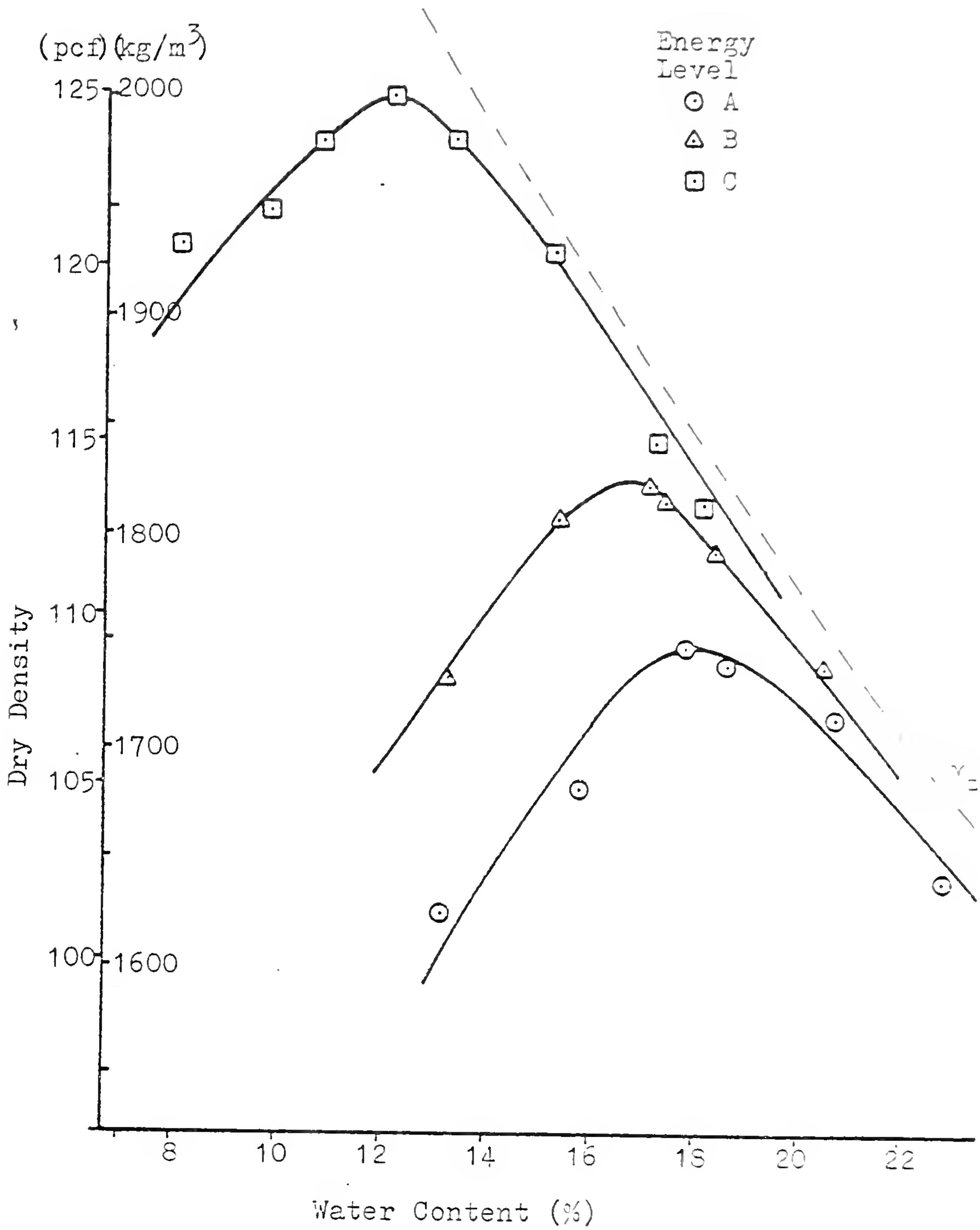


Figure 2.8 Impact Compaction Curves

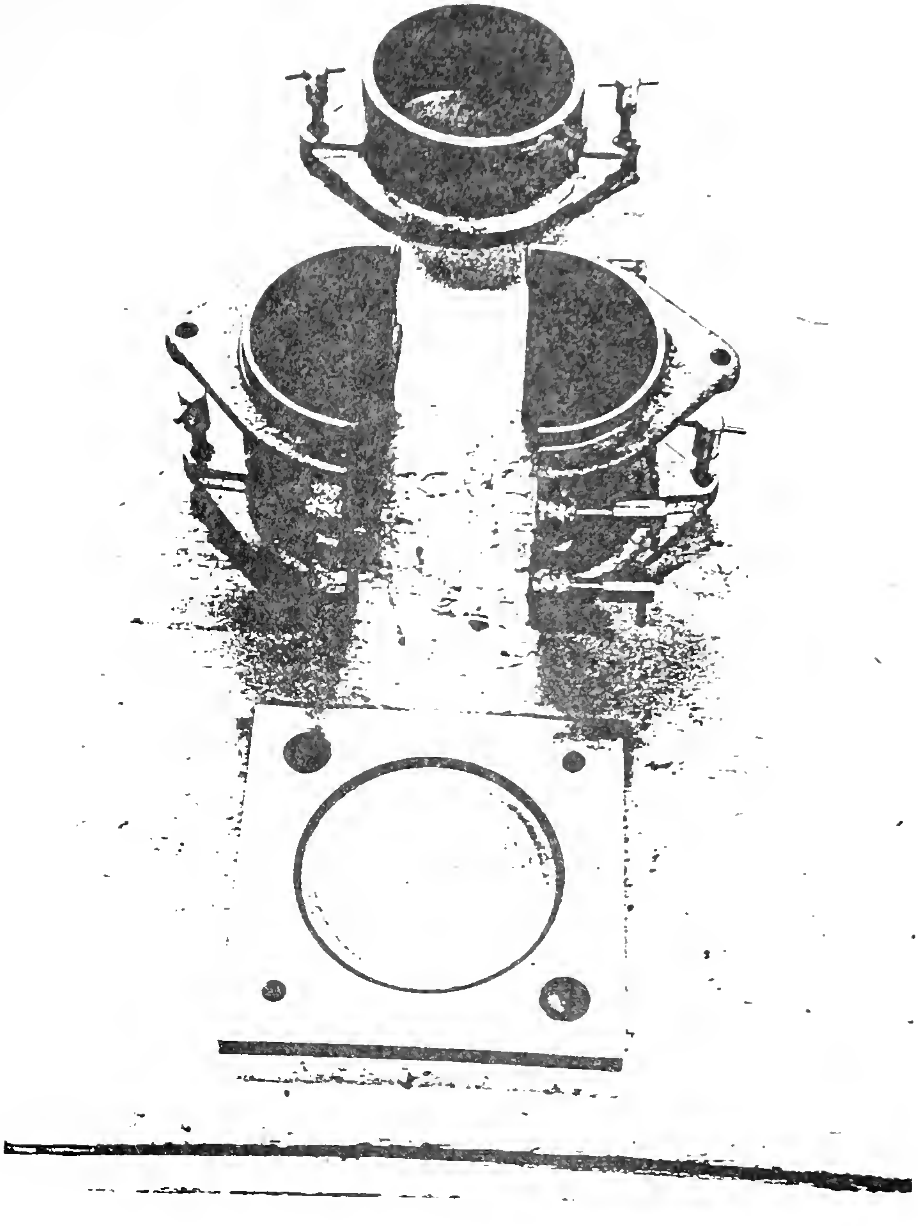


Figure 2.9 Standard Proctor Split Mold

Table 2.5 Density and Moisture Content Data for Laboratory Compacted Samples

Sample	w (%)	Dry Density (pcf)	Sample	w (%)	Dry Density (pcf)
I1A1	13.2	101.3	K1A1	13.1	99.1
I2A1	15.8	104.9	K2A1	14.3	102.7
I3A1	17.8	109.1	K3A1	16.3	107.2
I4A1	18.6	108.5	K4A1	18.5	110.6
I5A1	20.7	107.0	K5A1	20.1	108.5
I6A1**	22.8	102.2	K6A1**	21.7	104.7
I1B1	13.3	108.1	K1B1	12.7	105.9
I2'B1	15.4	112.7	K2B1	14.8	112.8
I2B1	17.1	113.6	K3B1	16.7	114.7
I3B1	17.4	113.2	K4B1	18.2	113.1
I4B1	18.4	111.7	K5B1	19.1	110.1
I5B1	20.5	108.4	K0*C1	8.1	114.9
I0*C1	8.1	120.6	K0C1	9.3	117.6
I0C1	9.8	121.6	K0'C1	10.9	119.7
I0'C1	10.8	123.6	K1C1	12.6	124.1
I1*C1	12.2	124.9	K2C1	14.4	121.5
I1C1	13.4	123.7			
I2C1	15.3	120.4			
I3C1	17.3	115.0			
I4C1	18.2	113.1			

**compacted only--not tested

removed, and the excess soil was trimmed away. The mold and soil were then weighed for density determination.

Impact Compaction

Impact compaction was chosen to prepare a second set of samples. The compaction procedure used was as specified in AASHTO T99 and ASTM D-698 and originally described by Proctor (1933). Three different energy levels were used in compacting the samples. For labelling and in order of increasing energy they were referred to as Low Energy Proctor (A), Standard Proctor (B), and Modified Proctor (C). Specific information regarding height of drop, weight dropped, number of layers, and number of blows per layer is presented for each energy level in Table 2.6

Table 2.6 Energy Levels for Impact Compaction

Energy Level	Compaction Method	Hammer Weight	Drop Height	Number of Layers	Blows/ Layer
A	Low Energy Proctor	5.5 lb	12 in	3	15
B	Standard Proctor	5.5 lb	12 in	3	25
C	Modified Proctor	10 lb	18 in	3	25

As with the kneading samples a Standard Proctor split mold was used to facilitate subsequent sampling of the soil in the mold. Soil handling, sampling for water content, trimming, and weighing were also done in the same manner as for the kneading compaction samples.

2-3.3 Tube Sampling

Tube sampling of the compacted mass in the Proctor mold was necessary to obtain a sample of the proper diameter for the companion study from which the pore size distribution samples were taken. Sampling was done using the same tubes used for collection of the field samples. Prior to sampling the four screws which hold the two halves of the split Proctor mold together were unscrewed. The mold was then held together for tube sampling with elastic surgical tubing wrapped tightly around the mold as shown in Figure 2.10. As the sampling tube was jacked in with a hydraulic jack, the halves of the mold were able to separate slightly but were still tightly held by the elastic tubing. Allowing this slight separation of the mold greatly reduced sample disturbance which occurred when not using the split mold. In Figure 2.10 the jacking operation is shown partially completed.

At this point, the laboratory samples were at a condition in the process identical to field samples after drive-tube insertion. They were then extruded from the tubes in the same manner as the field samples with the

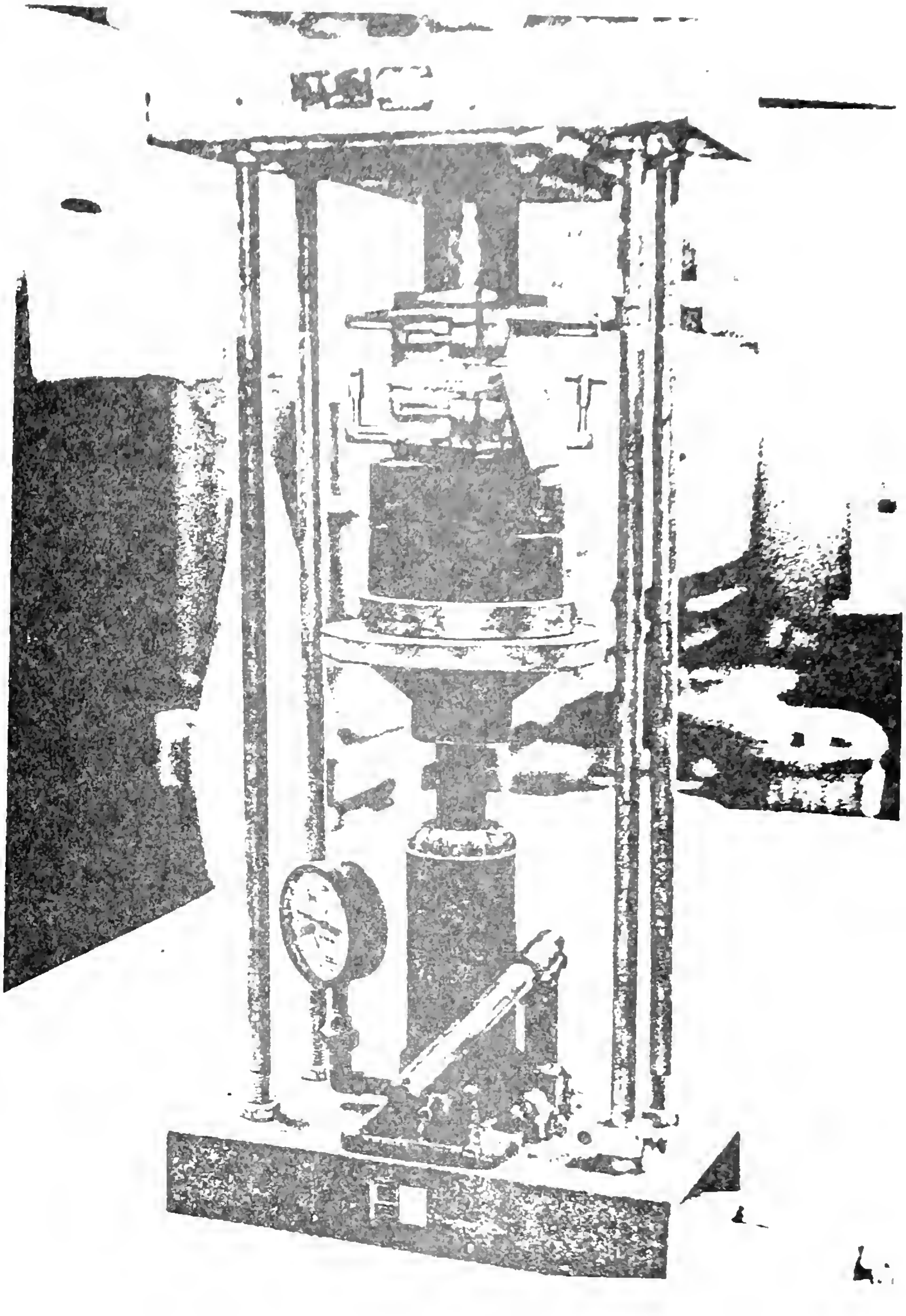


Figure 2.10 Sampling of Laboratory Compacted Samples

hydraulic jack and double-bagged in polyethylene bags for storage. To minimize moisture loss, the bags were then stored in a humid container. This storage method was used instead of the plastic-cheesecloth-paraffin coating process because storage time before testing was short. Storage time was, however, set at a minimum of 3 days to allow equilibration of moisture within the sample.

2-4 Trimming and Freeze Drying of Pore Size Samples

Samples to be tested using the mercury instrusion method to determine pore distribution are required to be of small size and contain no water. Therefore, trimming and drying operations were necessary to be able to test the tube-sampled soils obtained from both field and laboratory compaction procedures as previously outlined.

Tube samples were divided with a wire saw into two cylindrical pieces. The larger section was used in a companion study and was approximately 2/3 of the average 4 to 5 inch (10 to 13 cm) sample length in size. The smaller section, about 1/3 of the sample, was trimmed for samples for pore size distribution testing. On laboratory compacted samples, care was taken to insure that the lower third of the sample as oriented in the compaction mold was always the part used. In this way, approximately the same density of sample relative to the average density of the entire

mold was obtained consistently and the effects of variation of density from top to bottom of the compaction mold as discussed by Gau and Olson (1971) were minimized. With field compacted samples, it was impossible to consistently obtain the same section of the tube sample since orientation of the samples was not maintained in the storage facilities. Accordingly, a random distribution of top and bottom thirds was expected.

Samples were trimmed from the soil cylinder with a razor blade. This was felt to reduce the disturbance to the sample as Reed (1977) discusses. Samples were trimmed as near to cubic in shape as possible, and were dimensioned to approximately 1/3 inch (8.5 mm) on a side. This small size was necessary since (a) larger samples would very often crack during freezing, and (b) small samples were required to avoid exceeding the volume limits of the mercury porosimeter used for pore size distribution determination.

Freeze drying was successfully used by Ahmed (1971), Zimmie et al. (1976), Reed (1977) and Garcia-Bengochea (1978) among others to dry their soil samples for pore size distribution measurements. The procedure used was that of Zimmie et al. without the sample container cooling used by Ahmed which Zimmie et al. point out is unnecessary; cooling accompanied the sublimation process. Vacuum was maintained at approximately 0.1 mm of mercury for at least 10

hours (usually overnight) while sublimation took place. This time was felt to be quite conservative as noted by Reed (1977). The apparatus used for sublimation is shown in Figure 2.11.

Once sublimation was complete, the samples were removed from the wire cage and placed in glass bottles which were labeled and stored in a desiccator containing anhydrous calcium sulfate (known as "Drierite" commercially) which removed any remaining moisture.

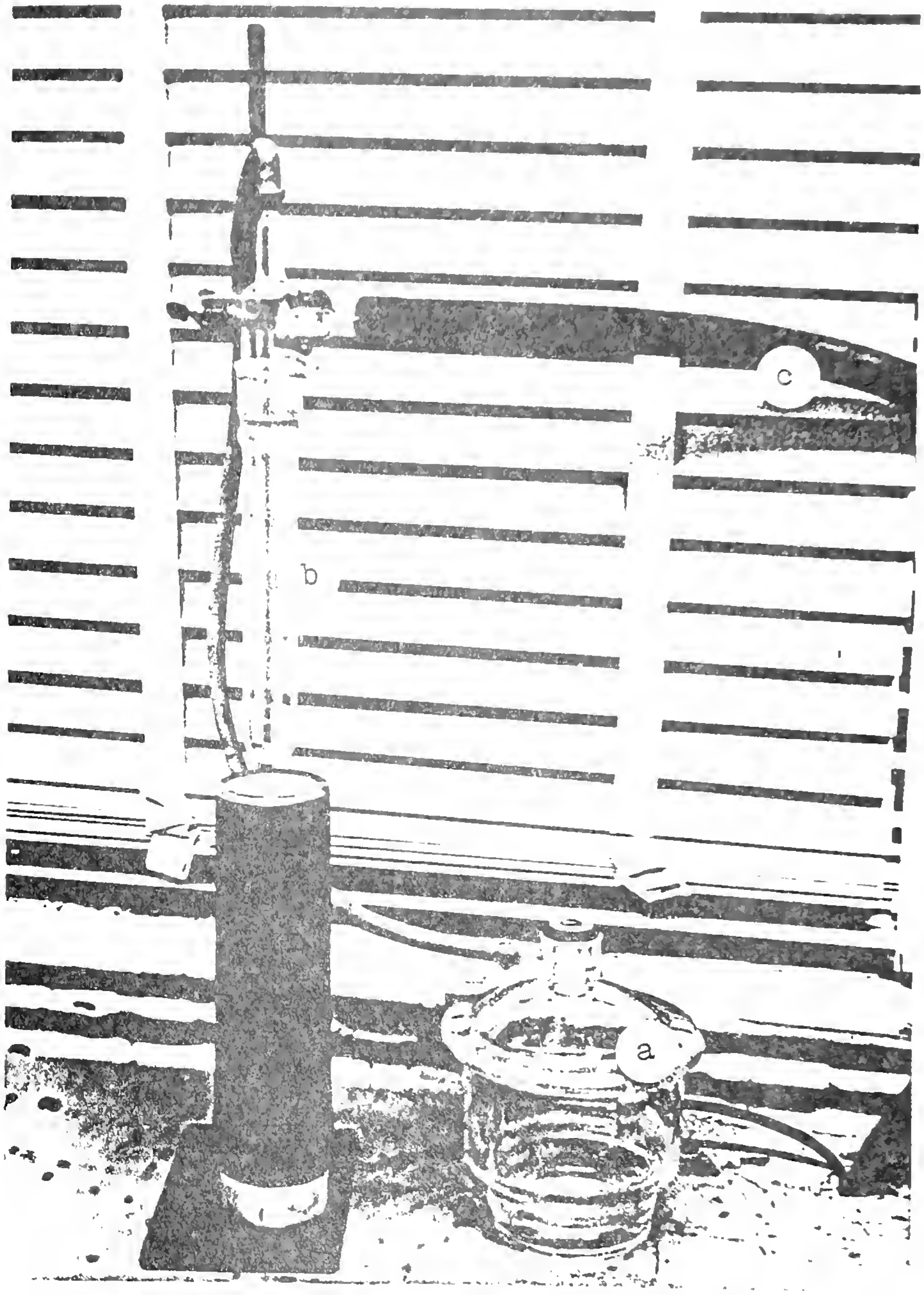
The degree of shrinkage of freeze dried samples was insignificant (4%) as was determined by testing a few initial samples. This agrees with reports by Reed (1977) and Garcia-Bengochea (1978) on the soils they studied. These small shrinkage values were found to also indicate that minimal sample disturbance had occurred (Tovey and Yan (1973)).

2-5 Determination of Pore Size Distribution

2-5.1 Apparatus

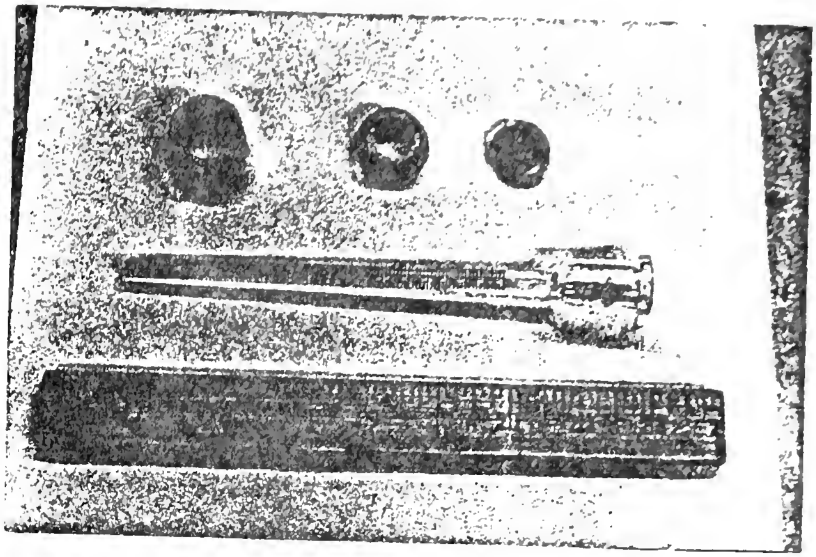
Apparatus used in measurement of pore size distribution include a penetrometer, a filling device, vacuum pump, McLeod gauge, mercury manometer, and control board; and an Aminco porosimeter.

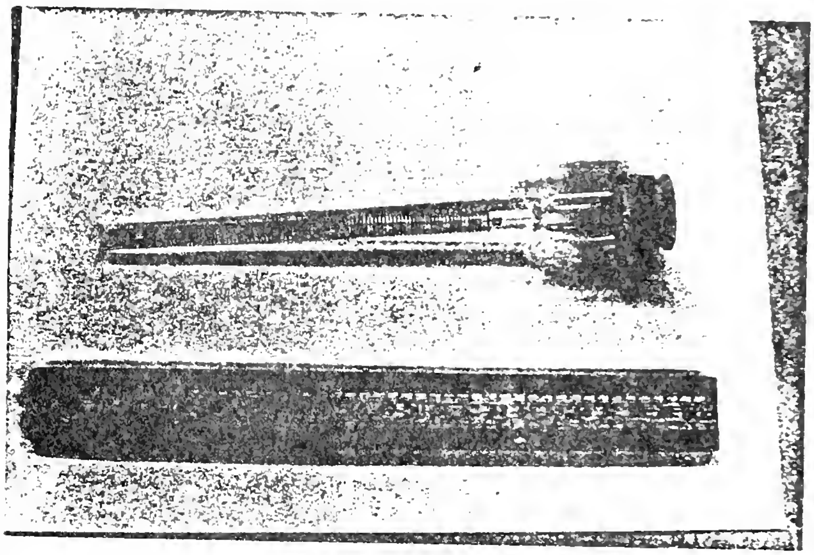
The penetrometer (see Figure 2.12) consists of a glass bulb attached to a finely calibrated capillary stem. The bulb is approximately 6.1 ml in capacity and is used



a - vacuum chamber
b - cold trap for water vapor
c - to vacuum pump

Figure 2.11 Sublimation Apparatus for Freeze Drying





top - penetrometer and cap disassembled

bottom - penetrometer assembly with sample in bulb

Figure 2.12 Penetrometer Assembly

to house the sample. It is sealed with a stainless steel cap which is greased and held on by a teflon fastener which fits over the bulb. The stem is calibrated in increments of 0.002 ml and has a capacity of 0.20 ml.

The filling device (see Figure 2.13) is a rotating, two armed glass tube manufactured by the American Instrument Co. which holds the penetrometer in a horizontal position during mercury filling and low pressure (below atmospheric) intrusion. A side chamber contains a mercury reservoir connected by a stopcock to the main tube. The filling device is connected through a control board to a vacuum pump, McLeod gauge, mercury marameter, and bleeder valve. The McLeod gauge is used to measure pressures below 1 mm of mercury and the manometer is used to measure pressures between 1 mm of mercury and atmospheric pressure. The arrangement of this system is shown in Figure 2.14.

Pressures above atmospheric are applied and measured by an Aminco porosimeter (see Figure 2.15). The porosimeter holds the penetrometer vertically in a chamber and applies pressures to 15000 psi with an electrically driven hydraulic pump using ethanol as the pressuring fluid. An electrical-mechanical sensing device capable of measuring volumetric increments of 0.0001 ml travels in the stem of the penetrometer. Intruding pressure is measured by two Bourdon pressure gauges of capacities 1000 psi and 15000 psi for use in the 0-1000 psi and 1000-15000 psi pressure ranges, respectively.

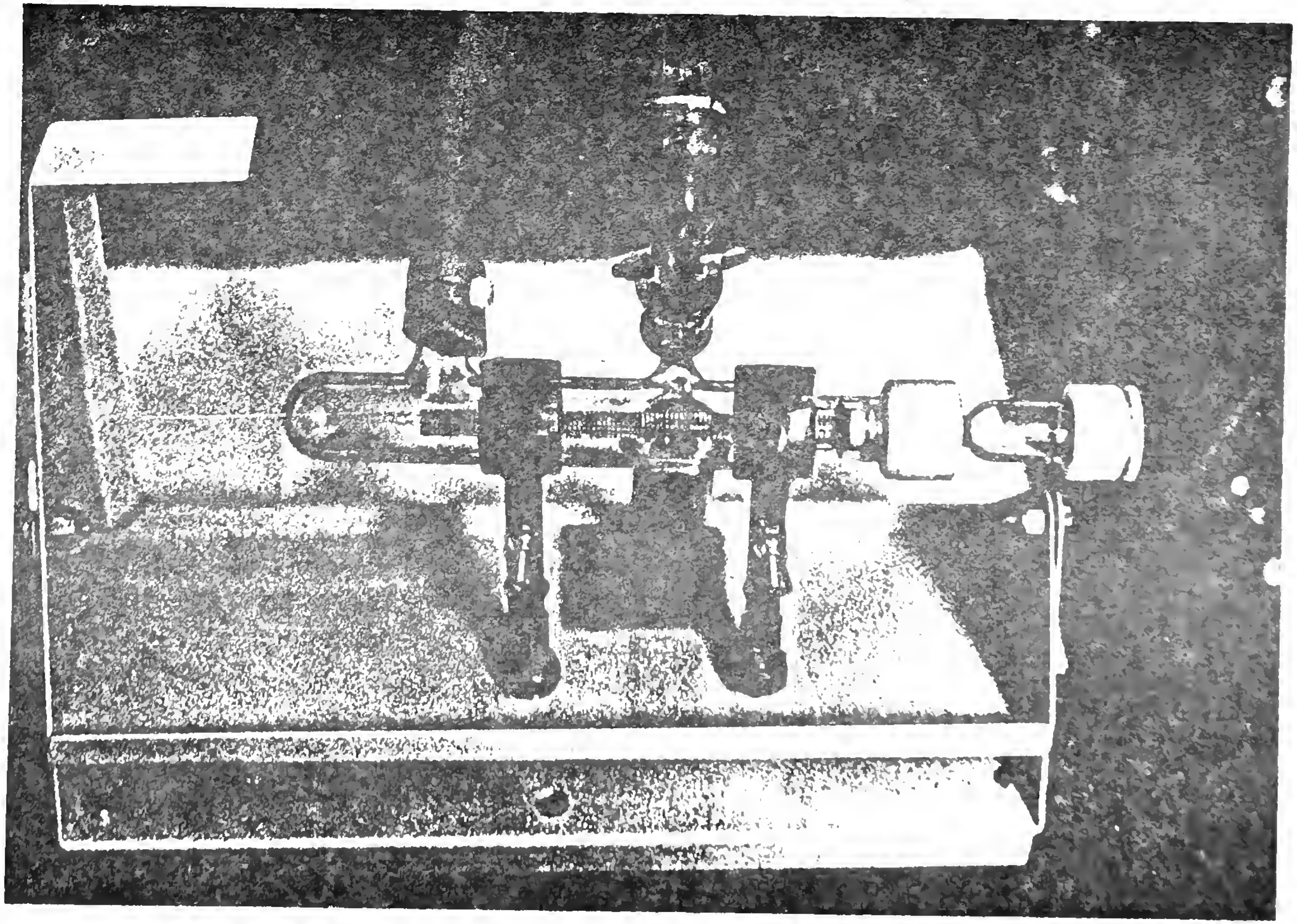


Figure 2.13 Filling Device

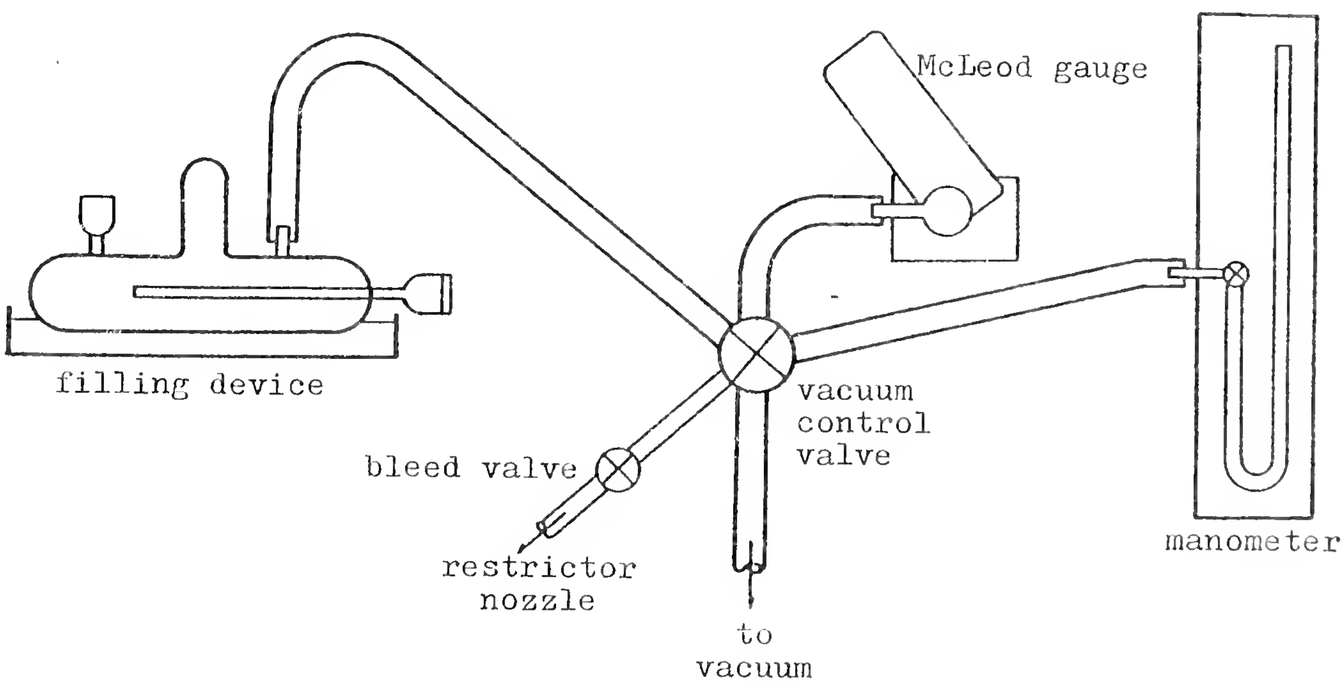


Figure 2.14 Control System for Low Pressure Intrusion

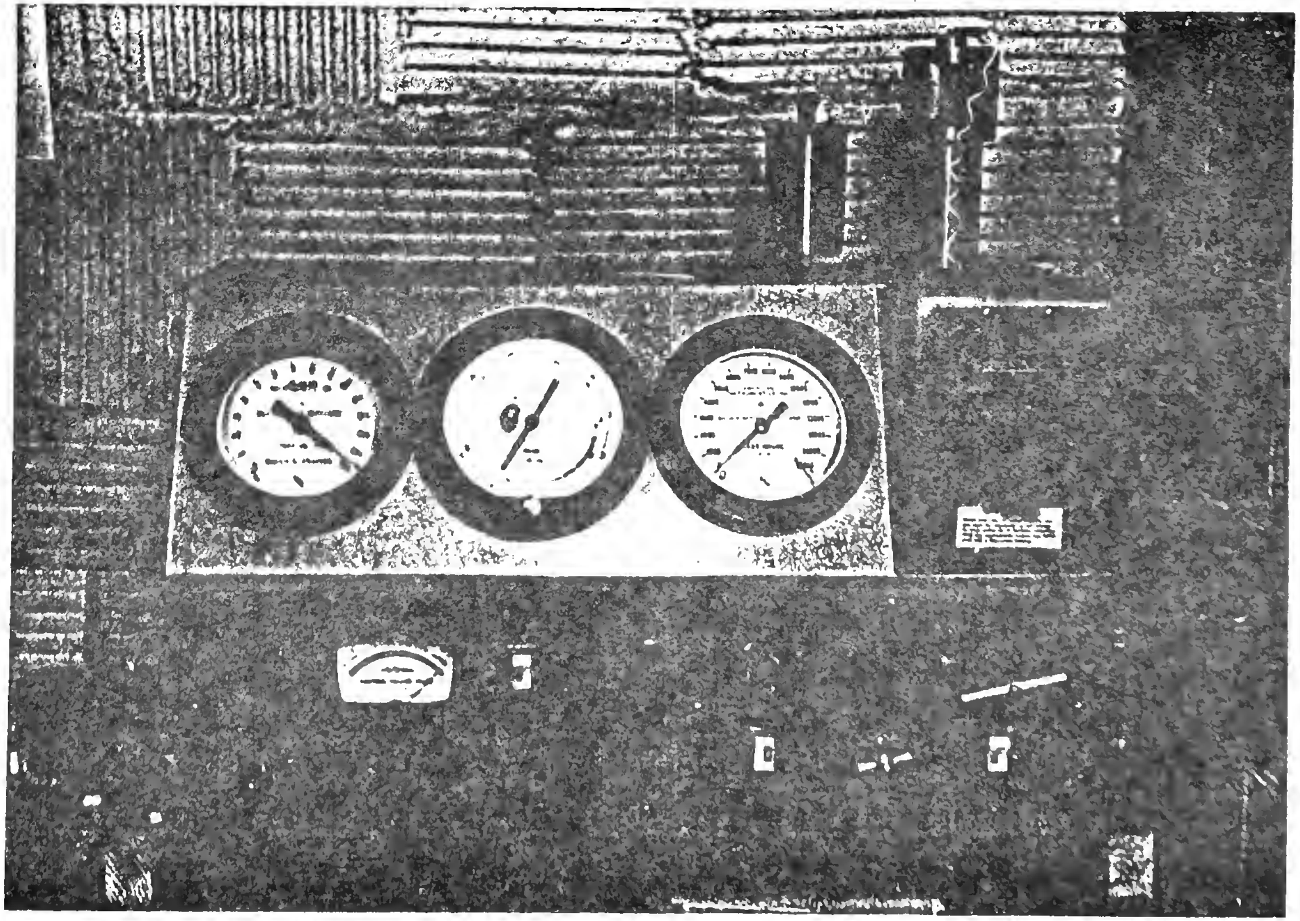


Figure 2.15 Porosimeter

2-5.2 Procedure

The test procedure used in this study was very similar to that used by Garcia-Bengochea (1978) and others before him. Therefore, the procedure will be outlined here and further discussion will be left to the references.

Following freeze drying, the samples were trimmed with a razor blade in a method intended to produce tensile failures on the surface and as a result keep surface pores from being smeared shut. After trimming, the sample was weighed to the nearest 0.0001 g, then sealed in the penetrometer and weighed again. The penetrometer was then placed in the filling device and sealed around the stem with the bulb protruding. This was a feature of the new manufactured filling device which allowed early detection of leaks in the penetrometer-cap seal. The vacuum pump was then used to evacuate the system to less than 0.20 ml of mercury, a process which usually took 30 to 45 minutes.

After evacuation of the system was complete, the penetrometer was filled with mercury. This was accomplished by rotating the filling device so that the mercury it contained covered the opening at the end of the penetrometer stem. The vacuum pump was then turned off and air was bled into the system to a pressure of approximately 20 mm of mercury. This pressure is known as the filling pressure. Raising the pressure forced mercury into the stem and into the bulb, surrounding the sample to be intruded.

After the mercury completely filled the penetrometer stem, the filling device was rotated again back to its original position. This broke off the column of mercury near the end of the stem producing an initial stem reading which was recorded along with the filling pressure. The pressure was then raised in increments according to the equation

$$\frac{P_i}{P_{i-1}} = 10^c$$

where c was approximately 0.20, to produce a logarithmically equal class width as suggested by Garcia-Bengochea (1978). This yields more even pore size distribution plots. This process was known as low pressure intrusion and was continued to atmospheric pressure.

When atmospheric pressure was reached, the penetrometer was removed from the filling device and weighed in order to find the amount of mercury in the stem. A final stem reading was taken with the axis of the penetrometer horizontal after which the device was rotated to vertical, another reading taken, and then placed into the porosimeter. An initial reading of volume intruded was taken using the electro-mechanical probe of the porosimeter. These steps allow for a transition from low pressure to high pressure readings. The pressure was increased incrementally maintaining intervals as for the lowest pressure readings until

the pressure was just below capacity of 15000 psi. Probe readings were taken after each increment of pressure was added. Only a short time (~ 15 sec) was found to be necessary to complete each incremental intrusion. This process (above atmospheric) was known as high pressure intrusion.

As noted in the literature review this procedure enabled measurement of pores from approximately 0.016 to 500 microns in size.

2-6 Data Reduction and Analysis

Computer plotting created differential and cumulative pore size distribution curves from the data taken from the measurements. Each curve was then analyzed for descriptor parameters which were assembled for use in a statistical analysis of the pore size distributions of the compacted soil samples.

The descriptors chosen to represent the pore size distributions of the samples were used as the dependent variables in a regression analysis as functions of compaction variables. Following checks for normality and homogeneity of variances of the descriptors, several analyses of variance were run to evaluate whether significant differences in the fabric existed (as evidenced by significant differences in the descriptors). Comparisons were made between impact and kneading compaction, Rascal and

Caterpillar compaction, and laboratory and field compaction procedures.

3 - RESULTS AND DISCUSSION OF RESULTS

3-1 Compaction

As mentioned previously, compaction curves were obtained for the soil compacted at three energy levels by each of four different methods of compaction (two laboratory methods and two field methods). These compaction curves are shown in Figures 2.2, 2.3, 2.7 and 2.8.

The two field compaction curves exhibited much scatter, and definition of an optimum water content and dry density was difficult. A certain amount of scatter was therefore to be expected for pore size distribution data from measurements on the field-compacted soil. The two laboratory compaction curves exhibited considerably less scatter; a smaller variability was also expected in the pore size distribution data for the laboratory compacted soil. The impact and kneading compaction curves matched up very well, verifying that DiBernardo's (1979) kneading compactor foot pressure values produce duplicates of the three impact compaction energy levels used. Densities obtained with the laboratory compaction methods were higher than those obtained in the field as was expected considering the differences between the laboratory and

field compaction procedures. The high energy level (C) in the field produced approximately the same densities as the low energy level (A) in the laboratory; the field optimum moisture content for this density was approximately 2% less than that found in the laboratory. The Caterpillar compactor produced slightly higher densities than the Rascal compactor for the same number of passes of the compaction equipment. This might be expected considering the heavier weight of the Caterpillar compactor (see Table 2.2).

3-2 Freeze Drying

The freeze drying process used was simple, replicable, and suitable for production use. After several initial measurements indicated minimal (< 4%) shrinkage volume change during freeze drying, no further checks were made on this since this small shrinkage suggests no sample disturbance has taken place (see Garcia-Bengochea, 1978).

3-3 Pore Size Distribution

For each pore size distribution determination the pressure and intrusion data were recorded and then punched onto computer cards. These cards were used in computer programs using the Purdue CDC computer to plot cumulative

and differential pore size distribution curves as plotted by a Calcomp plotter. These programs were modifications of those developed by Reed (1977) and are presented in Appendix B. The differential pore size distribution curve is the histogram and plots porosity frequency (% volume intruded for the pore diameter bandwidth as plotted at the mean diameter) on the ordinate and limiting pore diameter on the abscissa. A cumulative pore size distribution curve plots cumulative porosity (% volume intruded in pores of diameter larger than the given diameter) on the ordinate and limiting pore diameter on the abscissa. The cumulative curve may be obtained by integrating the differential curve. For each gross sample (as created by a given method of compaction at a specific water content and energy level to give a specific dry density) a porosimeter run was made on each of 4 replicate samples; each run was plotted individually to allow ready determination of the curve discriptors directly from the curves.

The pore size distribution curves for the soil tested were of the same general shape regardless of the method of compaction or of the water contents and energy levels used in compaction. On the differential pore size distribution curves a peak was evident, indicating a diameter at which a significantly greater volume of pores was found. This peak was found in different locations ranging over the five orders of magnitude of pore diameters

intruded; it varied greatly in magnitude (highest porosity frequency) and sharpness (number of adjacent diameters showing similar porosity frequency). Diameters smaller than the peak diameter tended to have a greater porosity frequency than diameters larger than the peak diameter.

Figures 3.1, 3.2, and 3.3 show a typical series of curves compacted by the same method at the same energy level over a range of water content values. The tendency towards finding more pore volume in larger pores when compacting dry of optimum is evident when comparing the dry side curve (Figure 3.3) to the at-optimum and wet side curves (Figures 3.2 and 3.1, respectively). Smaller peak size and less total porosity are also evident for the at-optimum curve as compared with other water contents.

Figures 3.3, 3.4 and 3.5 show a typical series of curves compacted by the same method at the same moisture content (relative to optimum) at three different energy levels. As the energy increases (Figure 3.3 to Figure 3.5) a reduction in total porosity is produced. This reduction seems to be at the expense of the pore volume around the peak diameter for the peak is much less evident in Figure 3.5, the curve for the soil compacted at high energy.

Comparison of Figures 3.5 and 3.6 shows the similarities which may be present among samples compacted by different methods (lab impact and lab kneading) with water content and energy level held constant; comparison of

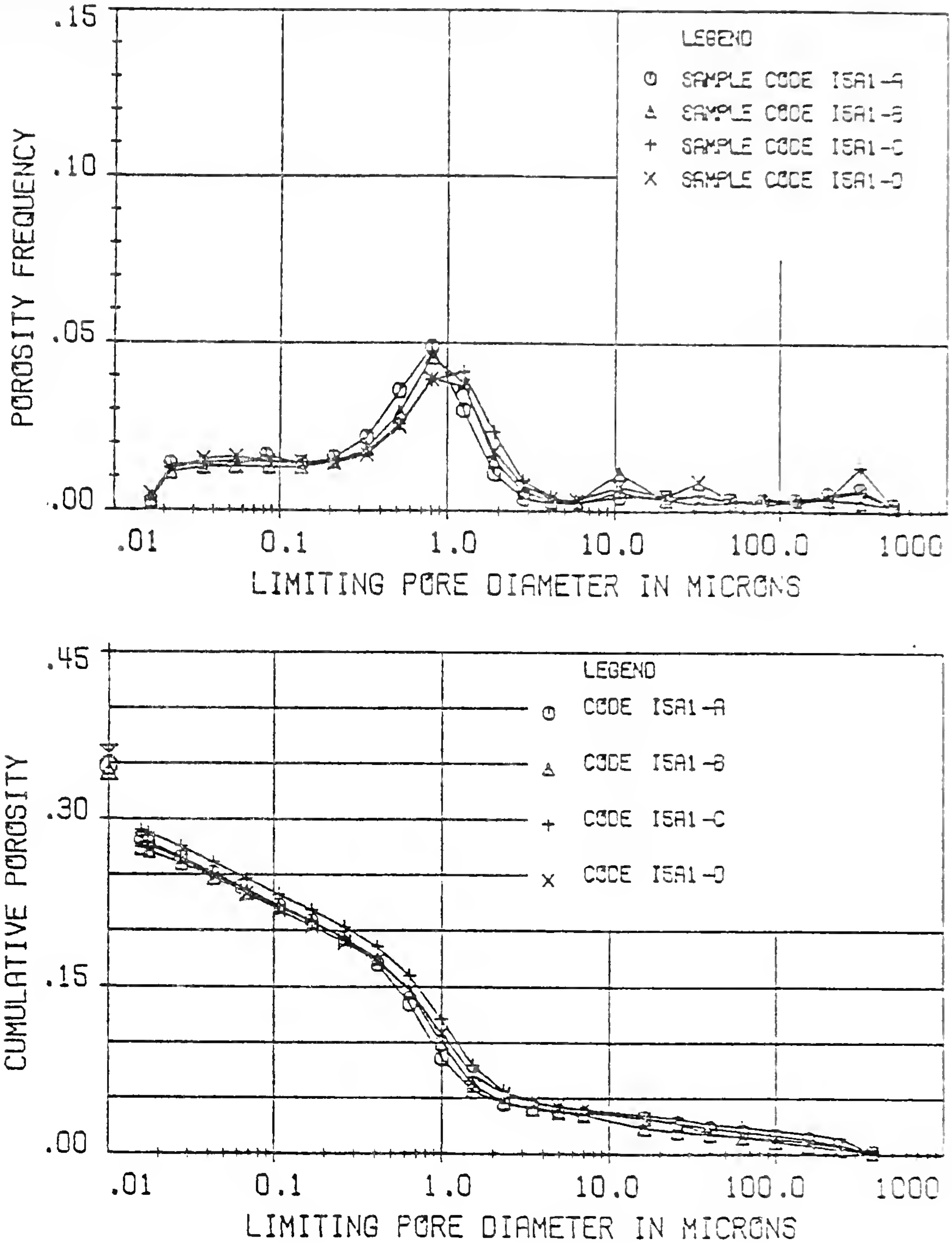


Figure 3.1 I5A1 Pore Size Distribution Curves

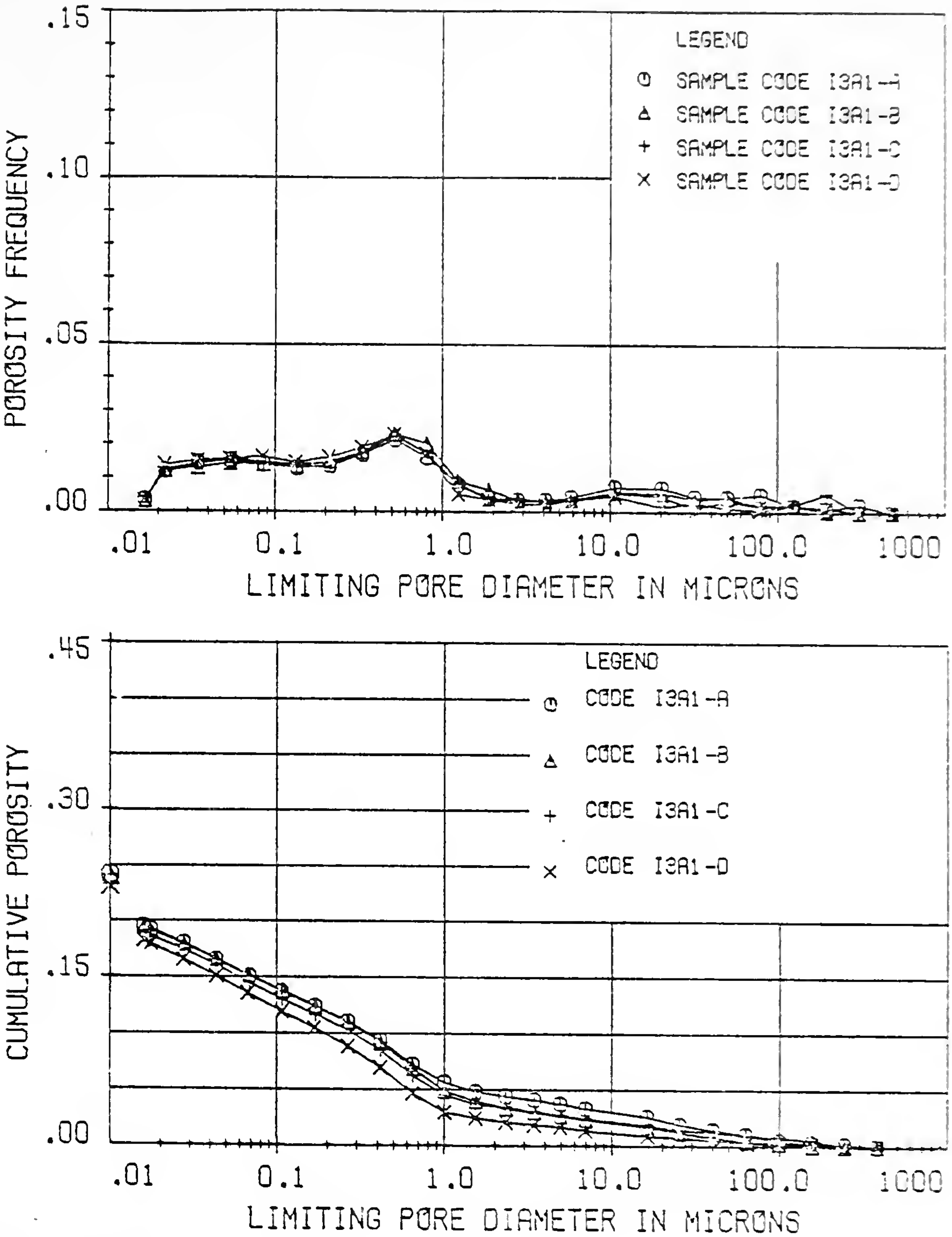
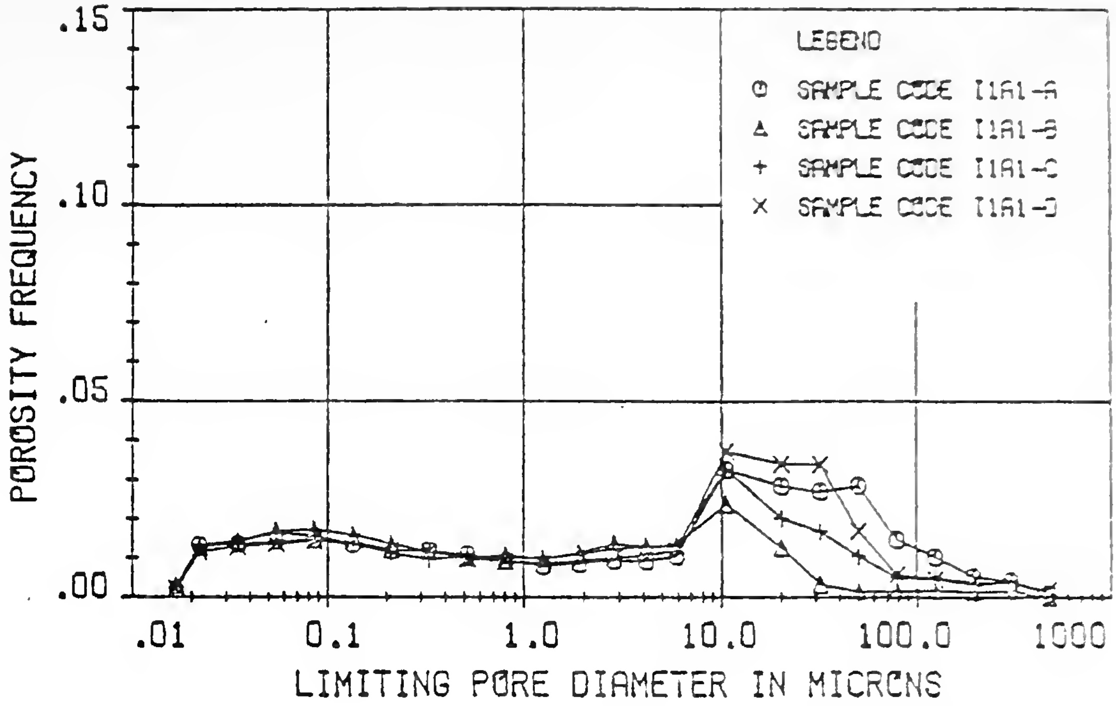


Figure 3.2 I3A1 Pore Size Distribution Curves



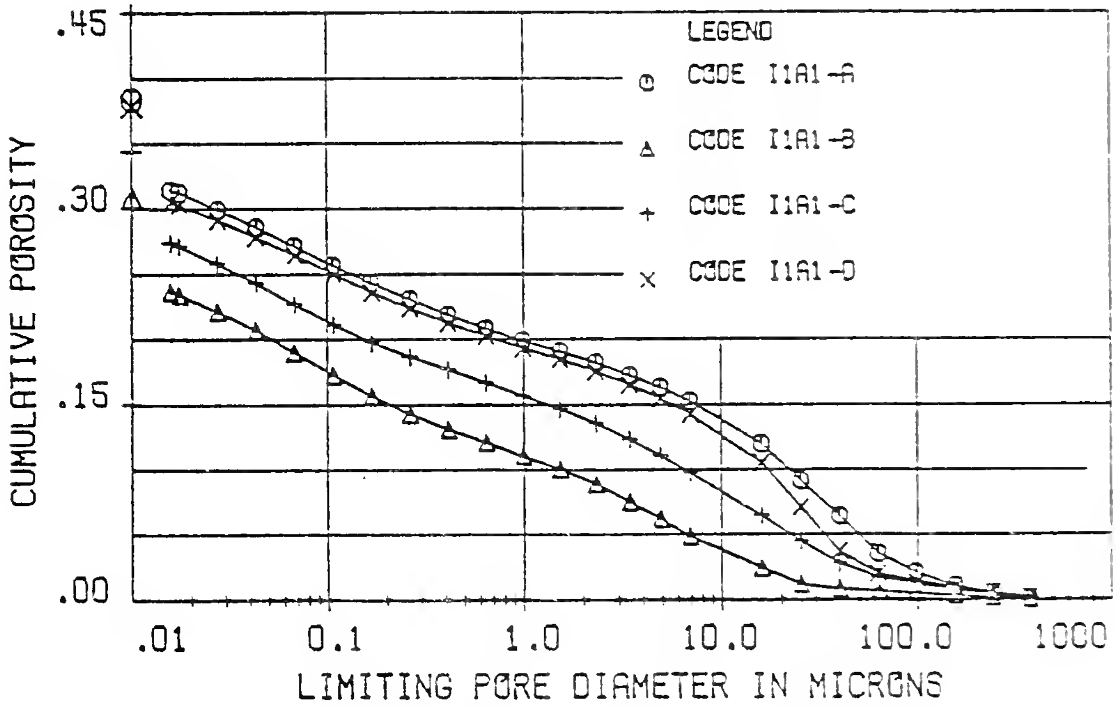


Figure 3.3 I1A1 Pore Size Distribution Curves

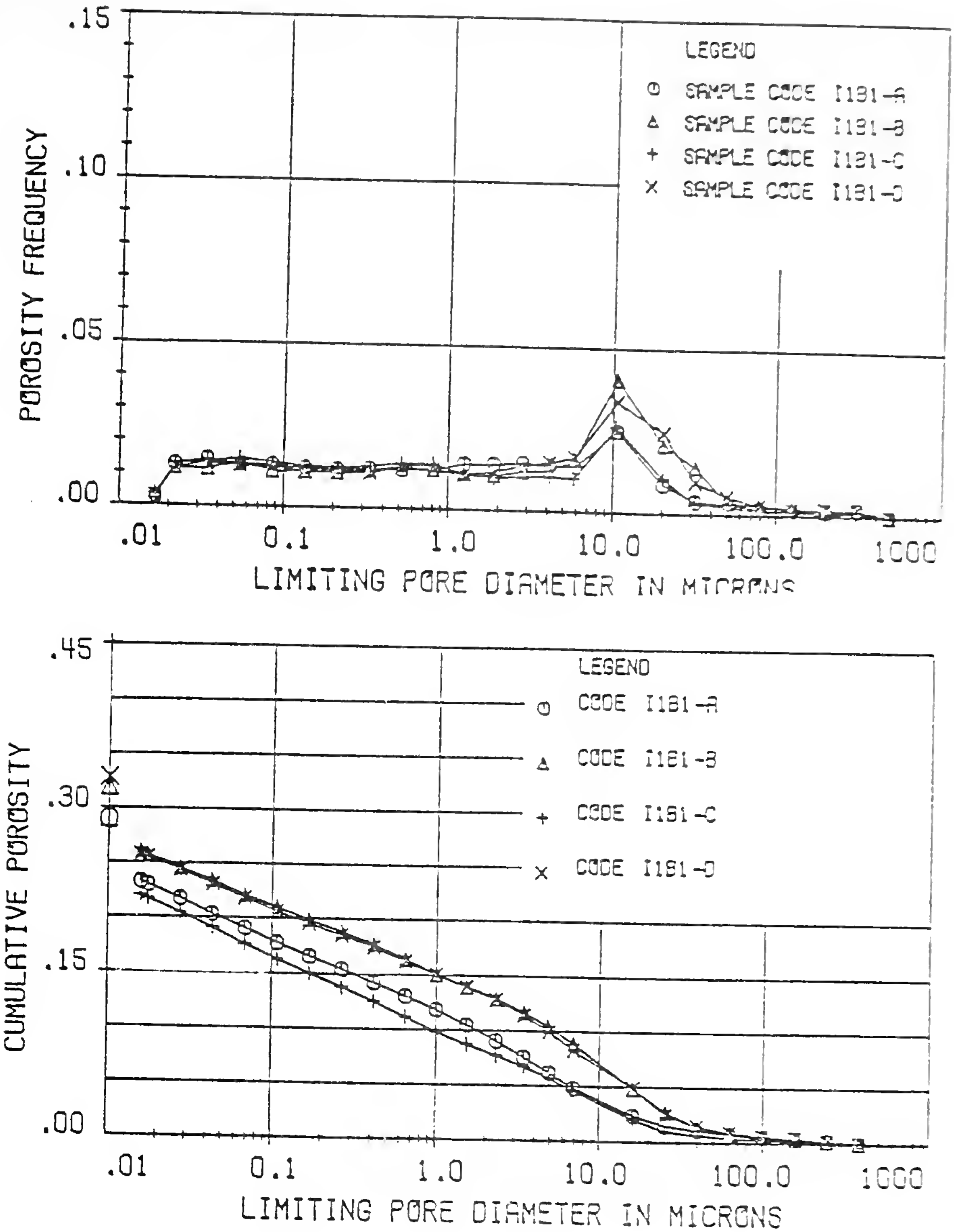


Figure 3.4 I1B1 Pore Size Distribution Curves

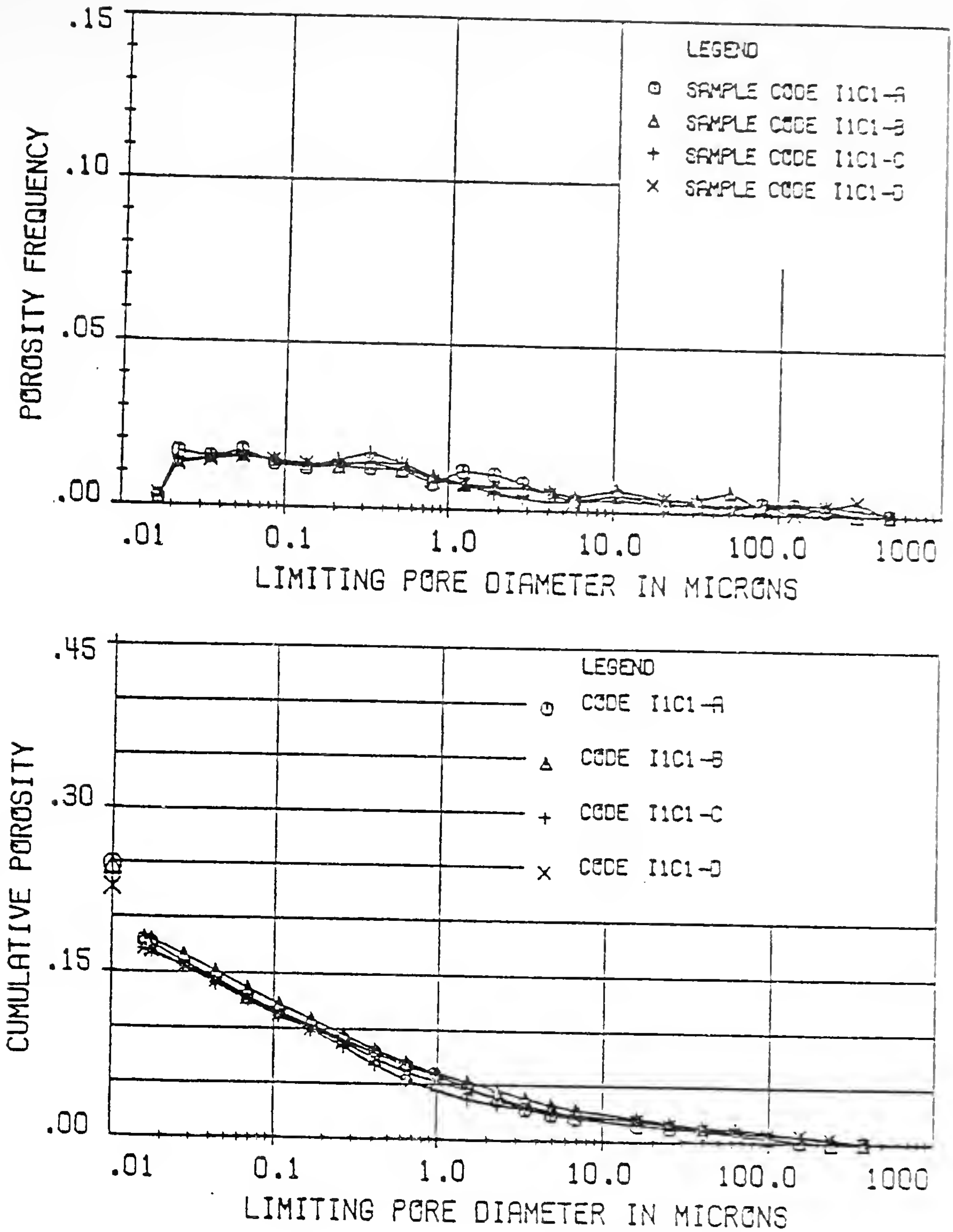
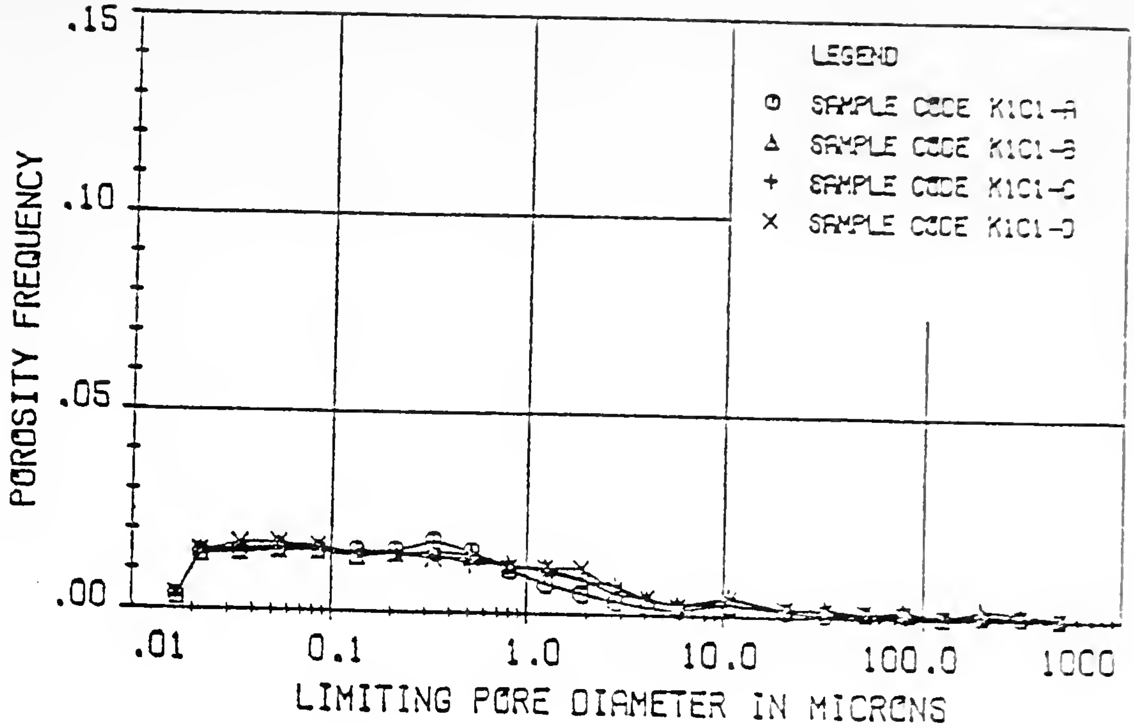


Figure 3.5 I1C1 Pore Size Distribution Curves



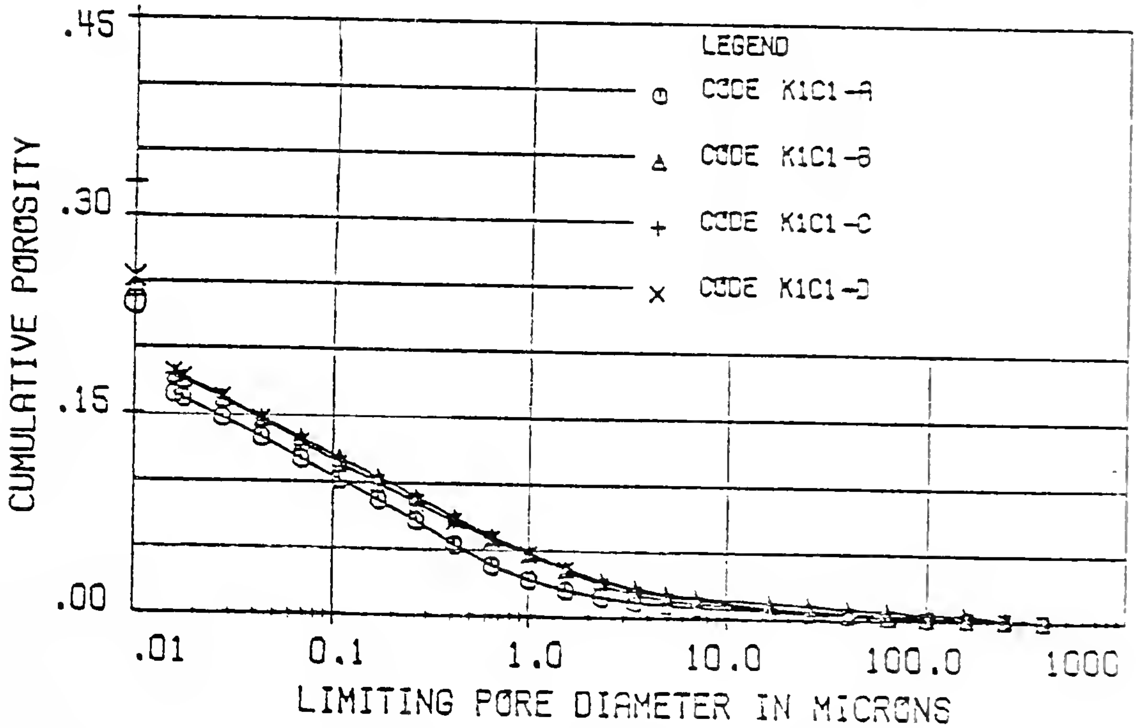


Figure 3.6 K1C1 Pore Size Distribution Curves

Figures 3.7 and 3.8 indicates that differences may also be quite evident between methods of compaction (Rascal and Caterpillar).

These general trends may only be examined qualitatively, however, so it was necessary to conduct a search for numerical parameters which effectively characterize the curves obtained for a given soil.

It should be noted that no bimodal distributions similar to those found by Garcia-Bengochea (1978), Reed (1977) and others were observed. This might be due to the fact that their soils were artificially created in the laboratory while this investigation studied a naturally occurring soil.

3-4 Choice of Fabric Descriptors

The parameters chosen by other authors (Table 1.1) served as a guideline in the solution of a large number of possible curve descriptors. Table 3.1 summarizes the complete set of descriptors and the method of calculation of each. Constructions made on the curves in Figure 3.9 show how some of the descriptors were obtained. M1, the maximum porosity frequency is the value of A on the top curve. L1, the peak diameter is found at B on the logarithmic scale of pore diameters. A1 and A2 are angles C and D, respectively in units of degrees; these angles were to measure the sharpness of the peak, and the lines defining

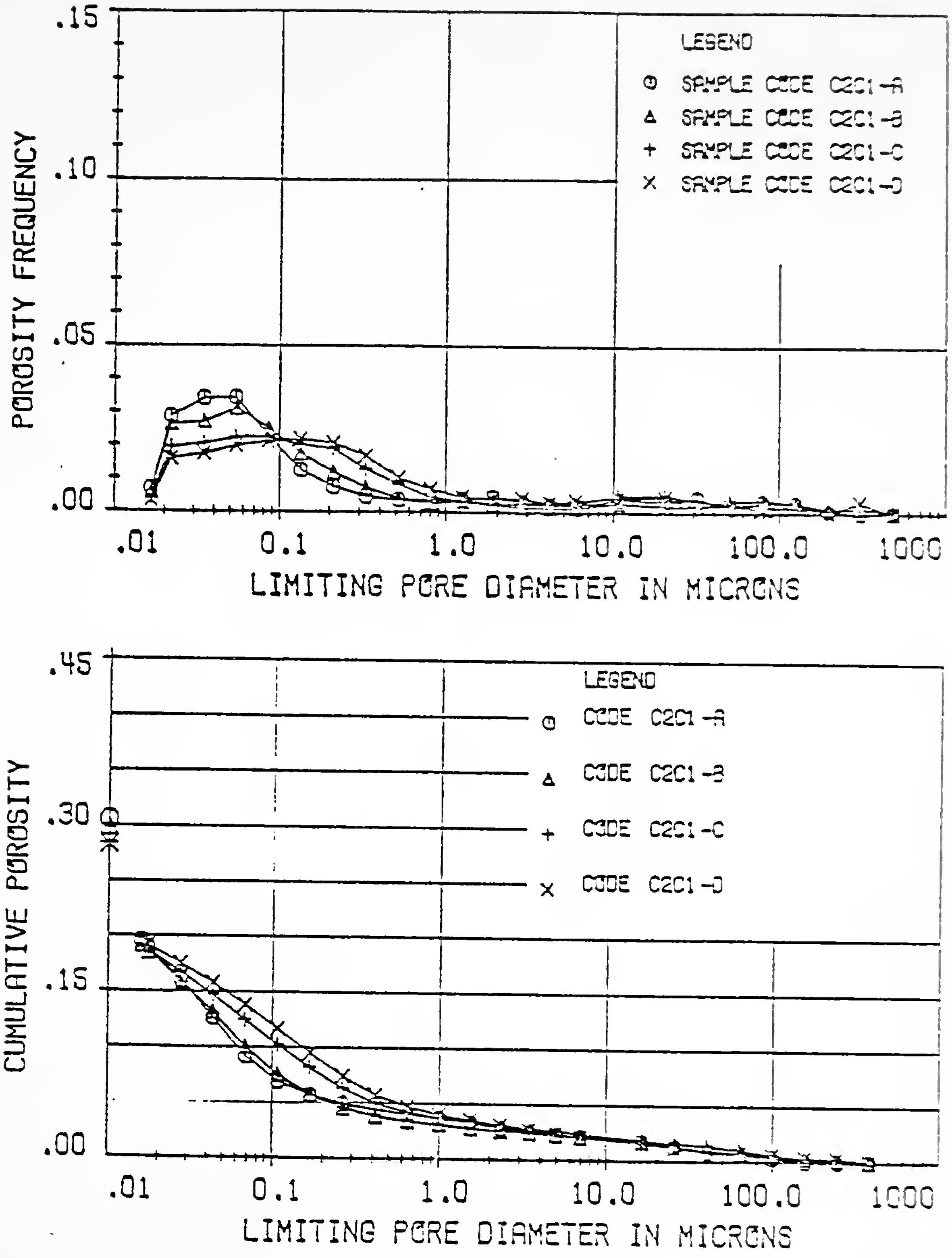


Figure 3.7 C2C1 Pore Size Distribution Curves

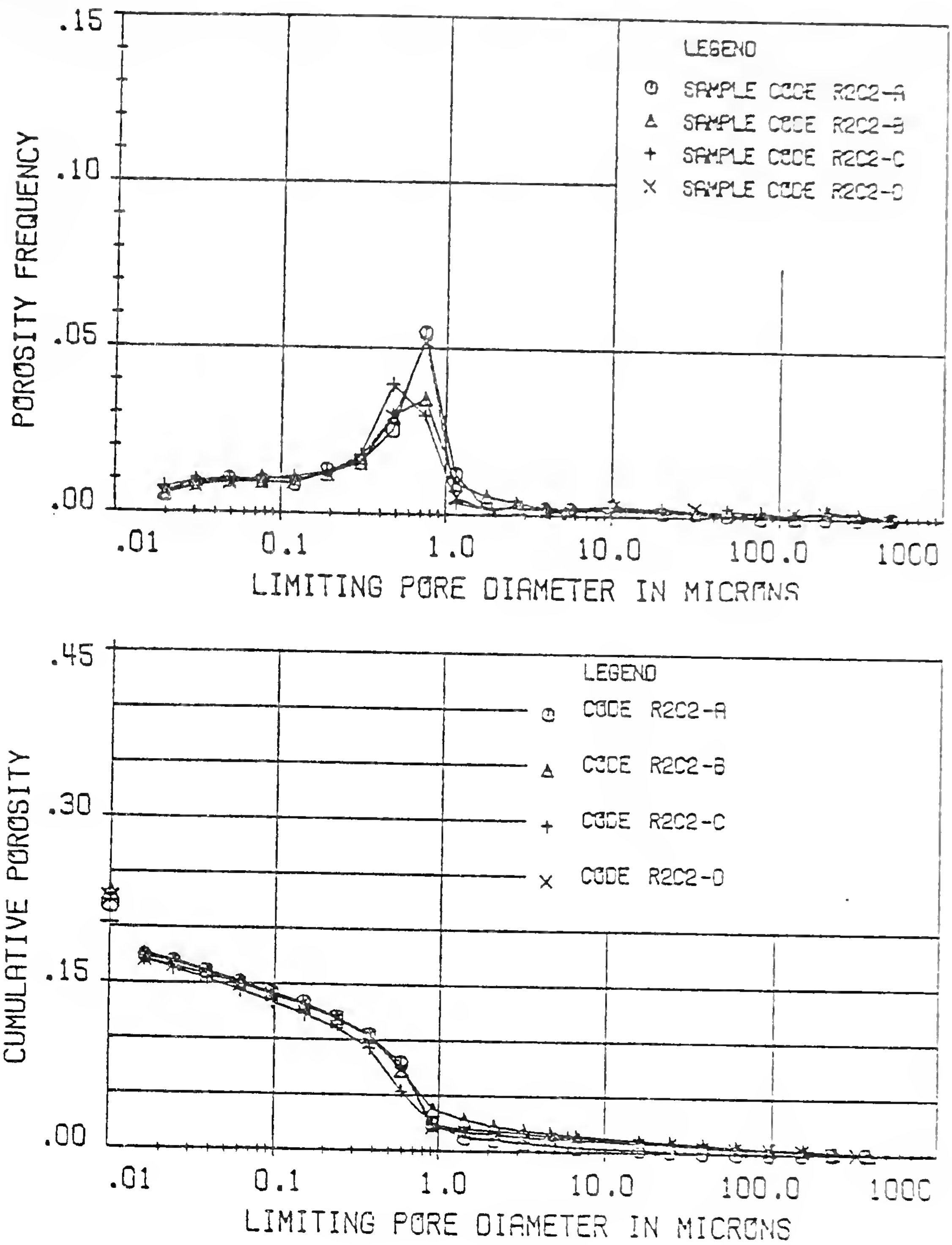


Figure 3.8 R2C2 Pore Size Distribution Curves

Table 3.1 Pore Size Distribution Curve Descriptors

M1	maximum porosity frequency
L1	log of diameter having maximum porosity frequency, "peak"
L2	log of diameter of "inflection point" where increase in porosity frequency to peak begins
A1	onset angle to peak on differential plot
A2	total angle difference at peak
P1	total porosity
P2	percentage of total porosity intruded
D2	log of diameter where 25% of intruded volume is in large pores
D3	log of diameter where 50% of intruded volume is in large pores
D4	log of diameter where 75% of intruded volume is in large pores
D5	log of diameter where 10% of intruded volume is in large pores
D6	log of diameter where 60% of intruded volume is in large pores
R1	ratio of 60% diameter/25% diameter
R2	ratio of 75% diameter/50% diameter
R3	ratio of 75% diameter/25% diameter
R4	ratio of 50% diameter/25% diameter
R5	L1 + R1
R6	ratio of inflection point diameter/peak diameter
R7	(50% diameter + 60% diameter)/25% diameter
X1	arithmetic value of L1,(10**L1)
X2	arithmetic value of D2
X3	arithmetic value of D3
X4	arithmetic value of D4
X5	arithmetic value of D5
X6	arithmetic value of D6
X7	arithmetic value of L2
PC1	percentage of intruded volume in pores larger than peak diameter

Table 3.1 (continued)

PC2	percentage of intruded volume in pores larger than inflection diameter
PC3	percentage of intruded volume in pores larger than 1 micron
S1	PC1 - PC3
S2	PC2 - PC3
S3	X3 + X6
S4	X1 + R2
S5	P2 + PC1
S6	P2 + PC2
S7	P2 + PC3

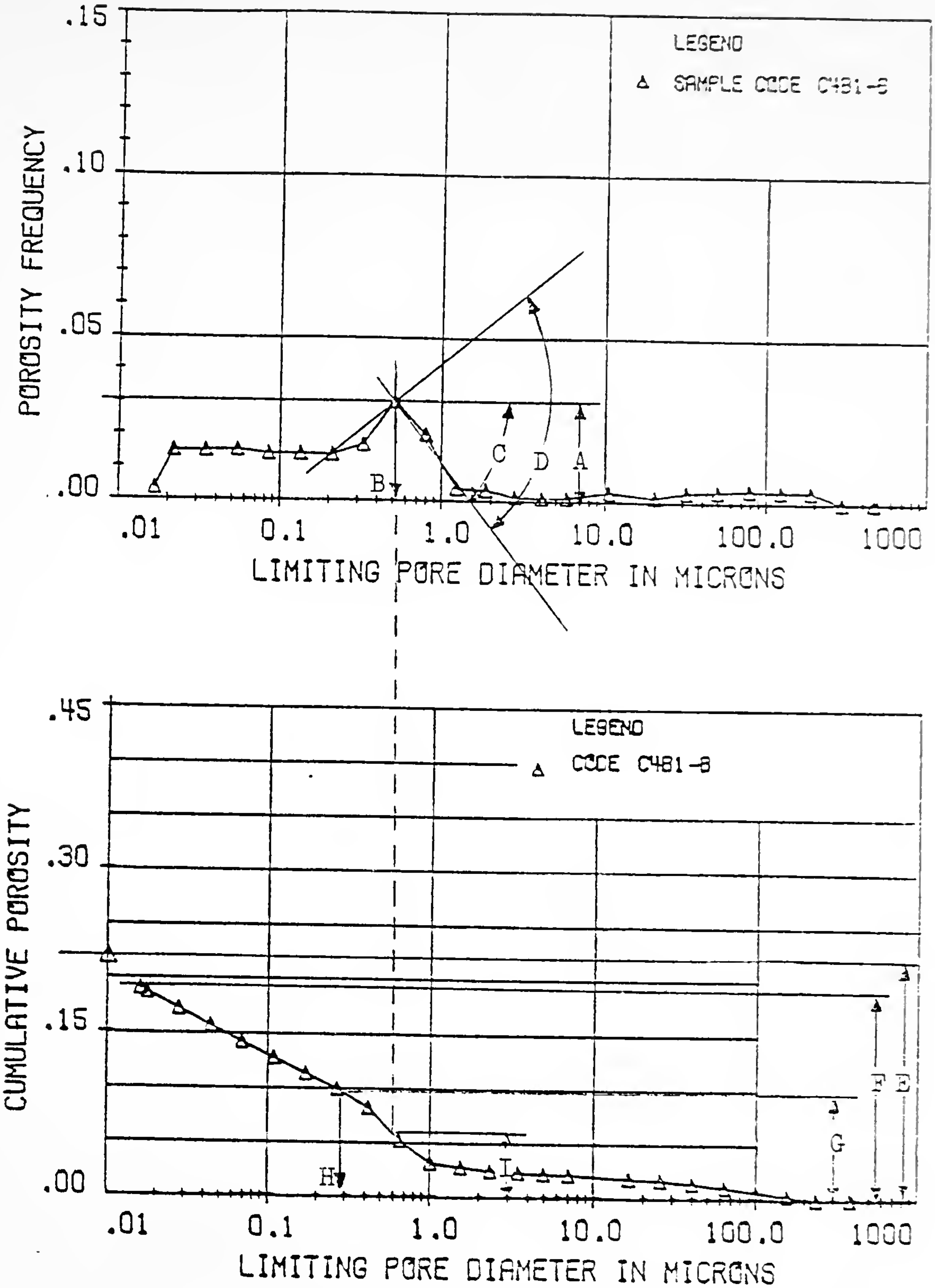


Figure 3.9 Constructions for Pore Size Distribution Curve Descriptors

these angles were constructed through points two data points to either side of the peak data point. P1, the total porosity, is the value of E on the bottom curve. P2, the percentage of total porosity intruded, is obtained by dividing the value of F by E. To find the 50th percentile diameter, D3, the value of E was multiplied by .50 to get the value of G; then, where the G value intersected the cumulative porosity curve, a vertical line was drawn which intercepted the logarithmic scale at H--the 50th percentile diameter (or D3). Other percentile diameters were found by similar means. PC1, the percentage of intruded volume in pores larger than the peak diameter was found by constructing a vertical line from the peak on the top curve down to intercept the bottom curve; the value of I, the intercept, was divided by F to get the value of PC1. Other descriptors involving percentages of volumes larger than a given pore diameter were found by similar means. Values for each descriptor for all of the pore size distributions curves are presented in Appendix A.

These descriptors were used as data in the statistical programs of SPSS -- the Statistical Package for the Social Sciences (Nie, et al. (1975)) -- on the Purdue University CDC 6500 - 6600 computer. Regressions were performed using the subprogram REGRESSION to find which of the descriptors were well related to the compaction variables. Data were subdivided into sets wet and dry of optimum

moisture content for each of the impact, kneading, Rascal and Caterpillar methods of compaction. Regressions using only water content, energy, and dry density produced poor results so interaction terms were added. Satisfactory results (based on acceptably high r^2 values--a measure of goodness-of-fit of a regression equation to the data) were found for some of the descriptors when using the following set of inedpendent variables

W	the molding water content relative to optimum
E	the energy of compaction, as a ratio to the lowest energy used for the method of competition

$W \times E$

W^2

$W^2 \times E$

This choice of variables was performed using the computer program DRRSQU which performs regressions on all independent variable subsets as discussed by McCabe and Arvesen (1974). Descriptors that were "acceptable" were required to have reasonably high r^2 values for each of the regression equations obtained for all four methods of compaction on either the dry side or wet side of optimum moisture content. It should be noted that the inclusion of terms involving the dry density did not improve the r^2 value of the regression equation significantly. The water content was found to be the most important

independent variable in the regression equations. This was also the case found by Ahmed (1971). The regression equations obtained for the descriptors found to be significant are presented in Table 3.2.

The variable PC3, the percentage of intruded value in pores larger than 1 micron in diameter, did not fully meet the r^2 criteria for an acceptable set of regressions. However, plots of PC3 versus W2, water content in relation to optimum, reveal that dry of optimum, more pore volume is found in the larger pores. These plots are found in Figures 3.10, 3.11, 3.12 and 3.13. This is the same phenomena found by Garcia-Bengochea et al. (1979) and others and seems to support the deformable aggregate soil model as discussed earlier. Difficulty in determination of the optimum moisture content in the field might explain the lesser tendencies found in the field curves, Figures 3.12 and 3.13.

Examination of the coefficients of the regression equations shows some similar results for the descriptors' relationship to the independent (compaction) variables among the different methods of compaction on the wet and dry sides of optimum. However, comparison of these equations in the W-E plane shows no clearly definable trends. Too many interactions are present to compare these curves by observation of coefficients alone. Comparison of the different methods of compaction is best done by other

Table 3.2 Regression Equations for Descriptors

Type of Compaction	Descriptor	w(W2)	E(E1)	wE(V2)	w^2(V3)	w^2E(V4)	Constant	r^2
		Regression Coefficients for						
Impact (Dry Side)	P2	-.0143	-.0151	-.00326	-.00328	-.000531	.820	.426
	D3	-.0521	-.0416	-.0203	.0319	-.00732	- .404	.686
	D4	-.0218	-.0264	-.00421	.00858	-.000963	-1.052	.598
	X4	-.00743	-.00417	.000151	.00251	-.000196	.0881	.567
	X6	.0232	-.0147	-.0115	.0464	-.00652	.221	.596
Kneading (Dry Side)	P2	.00553	-.0102	-.0155	.00173	-.00281	.780	.721
	D3	-.0136	-.0528	-.0184	.0290	-.0184	- .312	.807
	D4	.0543	-.0517	0.0598	.0149	0.00824	- .920	.774
	X4	.0172	-.0112	-.0162	.00444	-.00181	.121	.773
	X6	.109	-.0348	-.0938	.0426	-.0174	.320	.707
Caterpillar (Dry Side)	P2	-.142	-.0234	.0147	-.203	.0578	.800	.699
	D3	.183	-.131	-.176	-.375	.0518	- .200	.782
	D4	.388	-.0955	-.178	-.0344	-.0386	- .817	.781
	X4	.104	-.0212	-.0371	.0125	-.00811	.150	.676
	X6	.118	-.0573	-.0614	-.110	.0265	.356	.678
Rascal (Dry Side)	F2	-.800	.236	.544	-.364	.262	.419	.511
	D3	1.304	-.652	-1.359	.566	-.634	.392	.523
	D4	1.599	-.792	-1.595	.652	-.729	.0846	.674
	X4	.532	-.253	-.501	.215	-.229	.472	.604
	X6	1.009	-.526	-1.051	.418	-.483	.965	.603
Impact (Wet Side)	L1	.144	-.0957	-.0107	-.0412	.00688	- .127	.652
	D3	.286	-.0349	-.0379	0.0935	.0125	- .282	.687
	D4	.229	-.0284	-.0375	-.0657	.0103	-1.034	.604
	X6	.186	-.0174	-.0255	-.0524	.00788	.253	.565

Table 3.2 (continued)

Type of Compaction	Descriptor	Regression Coefficients for w(W2)	E(E1)	wE(V2)	w^2(V3)	w^2E(V4)	Constant	r^2
Kneading (Wet Side)	L1	-.0335	-.127	.238	.0734	-.121	- 0697	.767
	D3	.390	-.0600	-.0433	-.156	.0163	- .282	.893
	D4	.422	-.0056	-.138	-.213	.0745	- .890	.784
	X6	.836	-.0354	-.363	-.430	.197	.345	.838
Caterpillar (Wet Side)	L1	-.156	-.328	.111	.0155	-.0101	.220	.726
	D3	-.124	-.204	.0696	.0145	-.00741	- .123	.605
	D4	-.121	-.147	.0603	.0159	-.00772	- .786	.543
	X6	-.0438	-.0754	.0248	.00613	-.00317	.367	.455
Rascal (Wet Side)	L1	.685	.380	-.451	-.0839	.0566	-1.088	.808
	D3	.583	.323	-.348	-.0698	.0434	-1.205	.859
	D4	.424	.186	-.240	-.0535	.0313	-1.511	.747
	X6	.213	.0923	-.116	-.0271	.0154	- .0142	.600

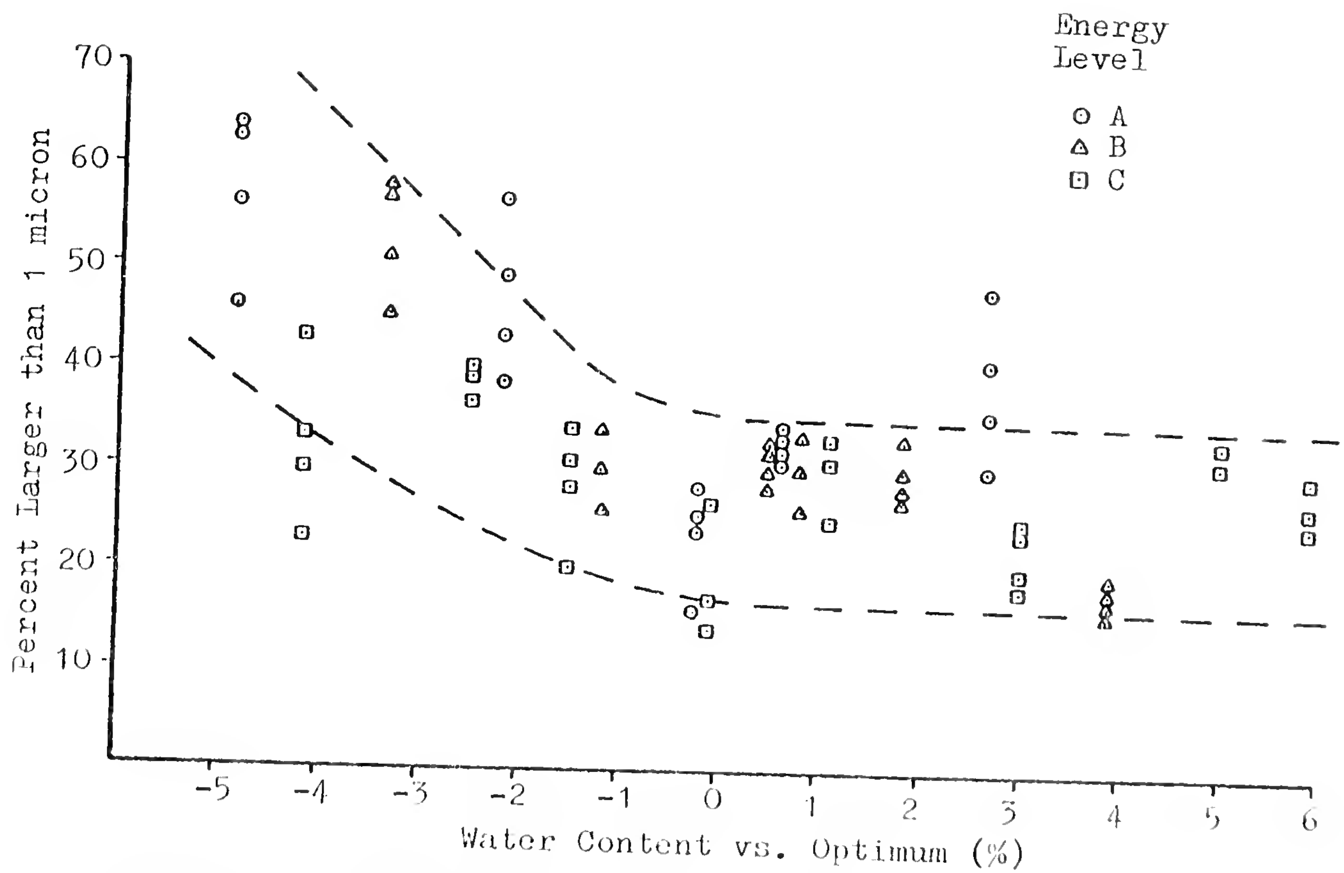


Figure 3.10 Percentage of Pore Volume in Pores larger than 1 micron vs. Water Content, Impact Compaction

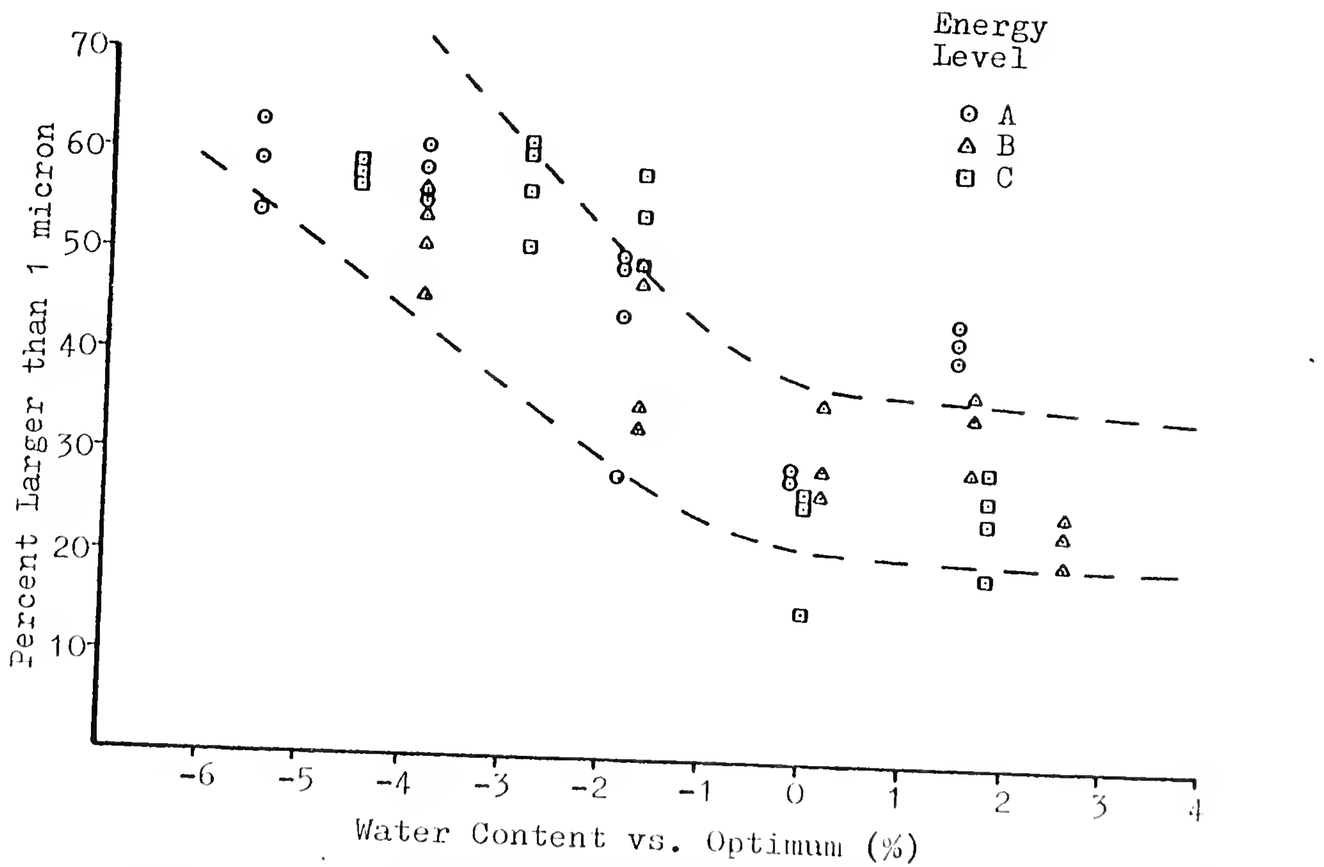


Figure 3.11 Percentage of Pore Volume in Pores Larger than 1 micron vs. Water Content, Kneading Compaction

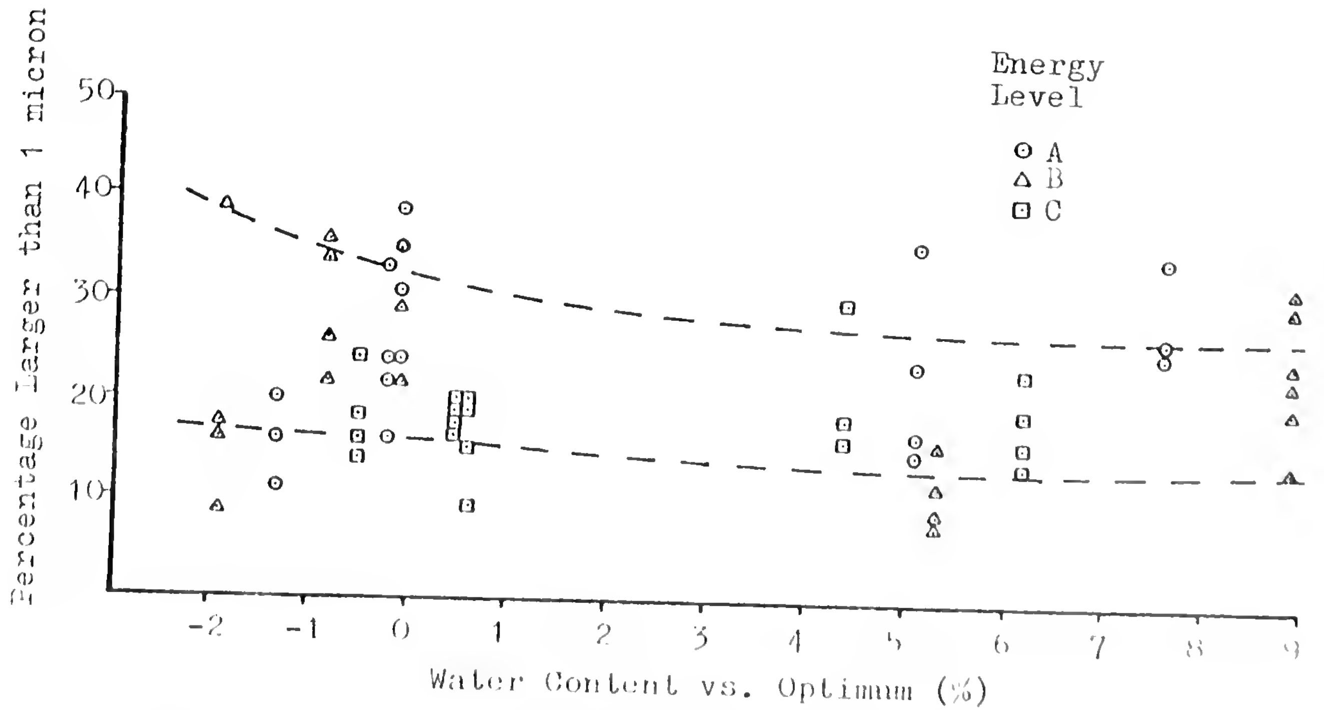


Figure 3.12 Percentage of Pore Volume in Pores larger than 1 micron vs. Water Content, Caterpillar Compaction

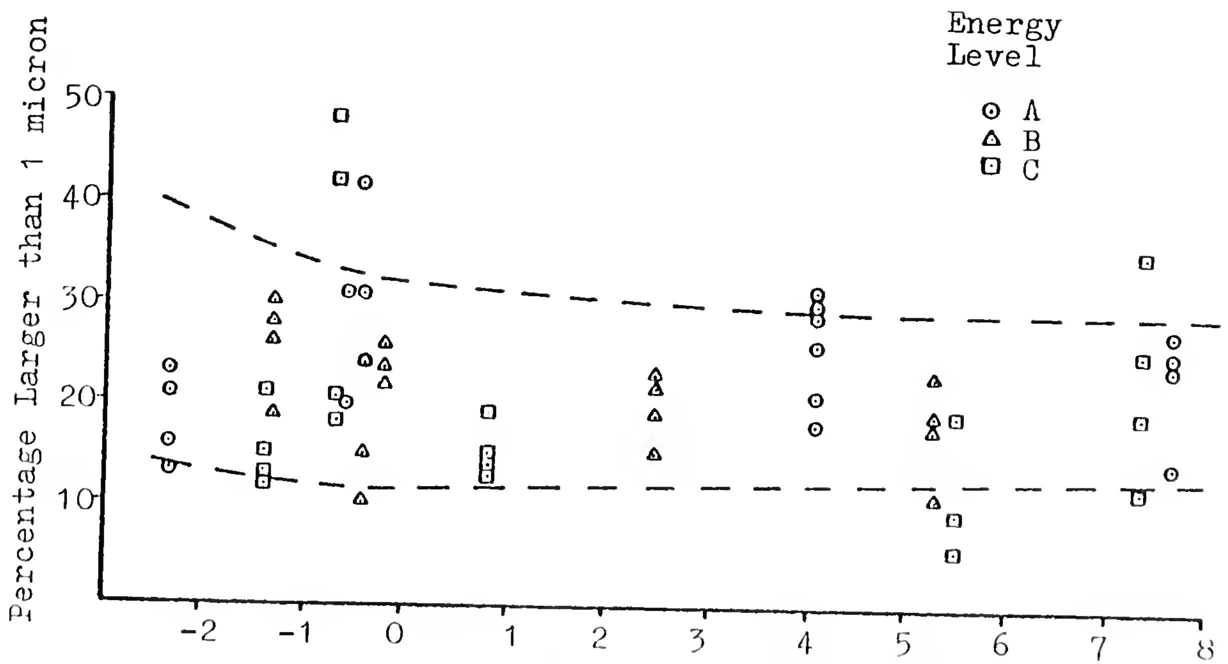


Figure 3.13 Percentage of Pore Volume in Pores Larger than 1 micron vs. Water Content, Rascal Compaction

statistical methods. This observation that interactions between compaction variables are important in describing soil behavior corroborates similar findings of Price (1978), Scott (1977), Essigman (1976), and others.

With the regression equations of Table 3.2 establishing significant relationships between the compaction variables and pore size distribution curve descriptors, one of the goals of this study was complete. It was desired then to establish whether, based on these descriptors, significant differences could be found between curves describing samples compacted by different methods.

3.5 Comparison of Fabric Descriptors

To compare the fabric as described by a set of the chosen descriptors, it was desired to use the SPSS subprogram ONEWAY, which performs a one-way or single factor analysis of variance on the data using a t-test. This method of analysis assumes normally distributed data and homogeneity of variances among the sets of data being compared. Therefore, the data sets of descriptor values were tested using the WTEST program based on the computation procedures found in Anderson and McLean (1974) for the W-test developed by Shapiro and Wilk to test normality. Data sets were also tested for homogeneity of variances by the Bartlett-Box F-test found in the ONEWAY subprogram. Levels of significance used were .01 for the W-test and .005 for

the Bartlett-Box F-test since the subsequent tests to be used were affected less by lack of homogeneity of variances. After subdivision of the data sets for each method of compaction into the four groups

(I) water content $\geq$ 1.5% wet of optimum, i.e., very wet of optimum

(II) water content $\leq$ 1.4% wet of optimum, i.e., wet side near optimum

(III) water content $\leq$ 1.5% dry of optimum, i.e., dry side near optimum

(IV) water content $\geq$ 1.6% dry of optimum, i.e., very dry of optimum

the normality and homogeneity of variances criteria were met for the descriptors P2, D3, and D4, i.e., the percentage of porosity intruded, the 50th percentile diameter, and the 75th percentile diameter, respectively. Other descriptors were eliminated from use since they did not meet the statistical criteria. The chosen descriptors were then compared using the one-way ANOVA program to assess whether significant differences in fabric occurred when using different methods of compaction. The mean values for the descriptors for the sets of data analyzed are found in Table 3.3.

Table 3.3 Mean Descriptor Values for ANOVA Data Sets

		Method of Compaction						
Variable	Case	IMPACT	LABORATORY	KNEADING	ALL	RASCAL	FIELD	CATERPILLAR
P2	I	.8000	.7855	.7637	.7922	.7818	.7970	.8121
	II	.7712	.7630	.7467	.7648	.7788	.7672	.7625
	III	.7555	.7522	.7467	.7602	.7779	.7649	.7518
	IV	.8055	.8054	.8053	.7885	.7025	.6788	.6550
D3	I	- .4071	- .3812	- .3419	- .4708	- .6171	- .5350	- .4529
	II	- .4446	- .4525	- .4683	- .4991	- .5150	- .5589	- .5765
	III	- .5425	- .5147	- .4683	- .4827	- .3504	- .4645	- .5786
	IV	- .0070	.0898	.1503	- .0312	- .5100	- .8175	-1.1250

Table 3.3 (continued)

Variable	Case	IMPACT	LABORATORY	KNEADING	ALL	RASCAL	FIELD	CATERPILLAR
D4	I	-1.0392	-1.0235	-1.0000	-1.0657	-1.1264	-1.0959	-1.0654
	II	-1.0729	-1.0805	-1.0958	-1.0966	-1.1375	-1.1171	-1.1090
	III	-1.1515	-1.1306	-1.0958	-1.0434	- .8729	- .9936	-1.1143
	IV	- 9375	- .8435	- .7847	- .9055	-1.1400	-1.3098	-1.4775

Method of Compaction (column heads IMPACT through CATERPILLAR)

case I $w \geq 1.5\%$ wet of optimum

case II $w \leq 1.4\%$ wet of optimum

case III $w \leq 1.5\%$ dry of optimum

case IV $w \geq 1.6\%$ dry of optimum

Comparison of the descriptor means using the SPSS subprogram ONEWAY produced the (statistically significant) conclusions that:

(1) for the very wet of optimum data, set I, laboratory fabric and field fabric are different

(2) for the very dry of optimum data, set IV, laboratory fabric and field fabric are different

(3) for the sets of data near optimum, II and III, no significant statements may be made, but tendencies indicate that differences between laboratory and field fabric exist

(4) for the dry of optimum data, sets III and IV, Rascal and Caterpillar compaction produce different fabric.

If two or three of the three descriptors showed significant difference at level $\alpha = .10$; then it was felt that this indicated that differences in fabric exist. The α-levels for all contrasts attempted are found in Table 3.4. An α-level below the level of significance of the test (.10) indicates that significant differences exist.

These data indicate that significant differences exist between fabrics of soil compacted in the field and fabrics of soil compacted in the laboratory. Lack of significance of these conclusions around optimum moisture content is most probably due to the difficulty experienced in establishing the optimum moisture content for the field

Table 3.4 Levels of Significance for Contrasts Comparing Fabric Descriptors

Data Set	Descriptor	Comparison Lab/Field	Impact/Kneading	Rascal/Caterpillar
I	P2	.430	.036	.201
	D3	.001	.323	.022
	D4	.062	.473	.287
II	P2	.777	.068	.662
	D3	.063	.683	.399
	D4	.412	.716	.582
III	P2	.222	.543	.076
	D3	.230	.183	.001
	D4	.000	.342	.000
IV	P2	.001	.990	.285
	D3	.000	.107	.028
	D4	.000	.002	.008

compaction cases. These differences between laboratory and field fabrics should certainly be expected since entirely different sets of shearing strains are imposed during laboratory and field compaction processes. Additionally, water migration accompanying consolidation is taking place on entirely different scales and in different sets of directions relative to the samples which were tested; this is due to the different confinement conditions of the soils during field and laboratory compaction.

No significant differences were found between impact compacted soil fabric and kneading compacted soil fabric for the soil tested. This supports the findings of Ahmed et al. (1974) in their tests on Grundite. The data from this study suggest that laboratory kneading compaction does <u>not</u> better simulate field compaction, at least from the fabric comparisons. This is contrary to suggestions discussed earlier, and indicates there is no preferred laboratory procedure for use in the prediction of field behavior.

It should be noted that contrary to the statement of Reed et al. (1980) for their soils, the soil tested in this investigation had unintruded pore space which was not "practically unimportant" but rather was an important descriptor of soil fabric. Note that the percent of unintruded pore space would be (1-P2), where P2 is one of the

three fabric descriptors used in the analyses performed. This unintruded pore space is most likely in a network of pores not continuous with the outside of the sample since the large volumes (up to 45% of the pore volumes) which were left unintruded would be difficult to account for in pores of very small diameter unreachable due to pressure limitations.

4 - CONCLUSIONS

For the soil studied (a residual medium plastic clay) and for the methods of compaction used:

1. The freeze dry-mercury intrusion method offers a simple procedure which can be used routinely to determine the pore size distribution of the soil.

2. The differential pore size distribution curves for all samples showed similar features even though samples were created by very different procedures. A peak diameter was found; about this diameter there is a greater volume of pores than at any other diameter. The diameter at which the peak occurred and the size of the peak changed as the method of compaction, water content, and energy of compaction were changed. No bimodal distributions similar to those of Reed (1977) and Garcia-Bengochea (1978) were found.

3. Curve descriptors involving the logarithm of the 50th and 75th percentile diameter and the percentage of the pore volume which was intruded were found to be most significant for use in pore size distribution curve comparisons.

4. The curve descriptors were significantly affected in magnitude primarily by the magnitude of the deviation of the compaction water content from the optimum water content for the respective sets of compaction variables which created the specimens. Compaction energy and energy-water content interaction terms were also significant. The inclusion of dry density in the regression did not have a significant effect upon the results.

5. The fabric of the laboratory compacted soils was significantly different from the fabric of the field compacted soils, as judged from quantitative comparison of the pore size distribution curve descriptors. The difference in fabric was more pronounced at water contents on the dry side and on the wet side of optimum. Differences were less pronounced near the optimum water content.

6. Laboratory compaction by the impact and kneading methods produced the same fabric.

7. Differences in the soil fabric existed on the dry side only (not on the wet side) between the Rascal and Caterpillar field compacted soil.

8. With the present sensitivity of pore size distribution descriptor values, it is now possible to quantitatively compare different fabrics produced by different compaction methods.

5 - RECOMMENDATIONS FOR FURTHER RESEARCH

This study has examined (through the measurement of pore size distribution) the fabrics of a soil compacted both in the laboratory and field over ranges of water contents and energy levels. Datahave been presented which indicate that certain descriptors can characterize the soil fabric and may be used in comparing soils compacted in different ways. This work should be extended as follows:

(1) Establish relationships to predict field pore size distribution curve descriptors from associated laboratory pore size distribution curve descriptors.

(2) Correlate the pore size distribution curve descriptors with engineering behavior properties in the field and in the laboratory. This can then lead to the development of prediction equations for field properties from the laboratory compaction variables.

(3) Investigate the nature of the unintruded pore spaces by using higher pressuring capacity porosimeter to intrude the soil samples. Establish whether the unintruded pore volume is in (1) pores

smaller than the capacity of the porosimeter used or (2) pores not continuously connected to the exterior of the sample.

(4) Perform pore size distribution measurements on a large variety of soil types compacted in both the laboratory and field; this is intended to broaden the sensitivity of the pore size distribution as functions of all the variables.

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APPENDICES

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